THE SEARCH FOR

ALIEN WORLDS

YOUR COMPLETE GUIDE TO EXOPLANETS

All About Space

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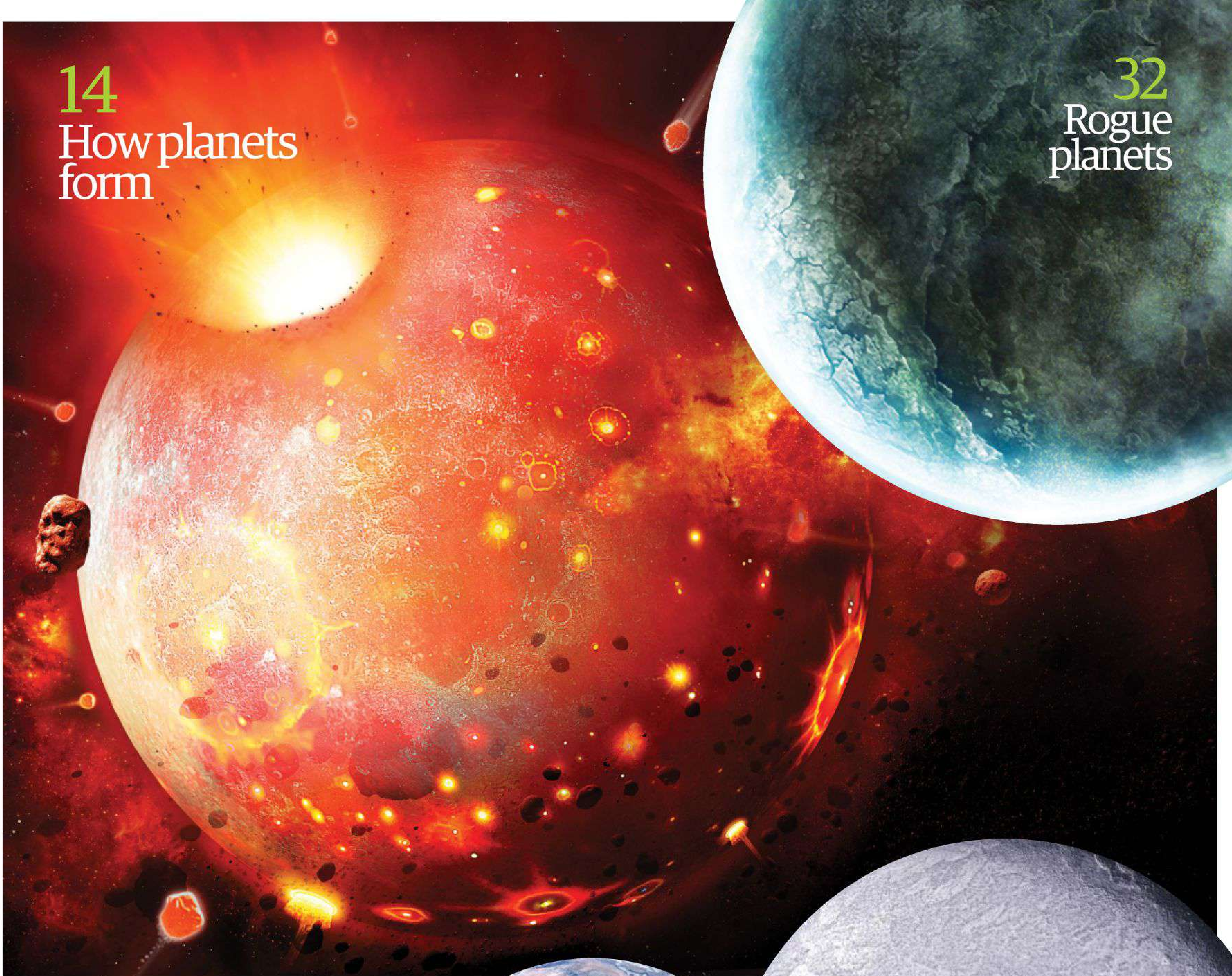


10 AM EXOPL

AZING ANETS

Until the early 1990s the only known planets were those in our Solar System. Astronomers have since identified more than a thousand alien worlds. **All About Space** brings you the 10 most wonderful exoplanets discovered by humanity… so far

Where you will find our ten best exoplanets

4. HIP 11952b
At 12.8 billion years old, this newcomer to the exoplanet scene is the golden oldie of our selection.

6. Kepler-64b
A little bit larger than Neptune, this is the first planet found in a four-planet system 5,000 light years away in Cygnus.

8 KOI-55b
One of two planets orbiting an aged star that will become a white dwarf, 3,850 light years away in Cygnus.

9. HD 40307g
The best chance for a potentially habitable planet is this one, a rocky world seven times the mass of Earth, 42 light years away in the constellation Pictor.

3. Kepler-42d
126 light years distant, Kepler-42d transits a red dwarf in the constellation Cygnus along with two other planets, all smaller than Earth.

1. HD 69830b
A super-Earth orbiting an orange dwarf star 42 light years away in the constellation Puppis.

The Sun
Most exoplanets orbit a star just like our own Solar System.

2. HAT-P-32b
Just over 1,000 light years from Earth in the constellation Andromeda, this enormous gas giant has swollen to twice the diameter of Jupiter.

7. WASP-12b
This planet, the hottest known, is found orbiting a Sun-like star 800 light years away in Auriga.

10. Omi CrB b
Around 270 light years away, this planet has a mass 1.5 times greater than Jupiter's and orbits an orange star in Corona Borealis.

5. Alpha Centauri Bb
The closest exoplanet is this super-Earth orbiting Alpha Centauri B, a short hop from the Solar System at 4.2 light years.

1 Biggest super-Earth

HD 69830b

Size: 10 times that of Earth
Distance from Earth: 41 light years
Type: Super-Earth
Most like: Earth x10

When it comes to super-Earth planets, you cannot get any bigger than heavy-weight world HD 69830b. Roughly 10 times more massive than our home planet, this rocky world is arguably the largest exoplanet in super-Earth flavour that has so far been uncovered in our high-tech hunt for alien worlds around distant stars. Orbiting its 41 light-year distant orange dwarf star, HD 69830, which rests in the constellation of Puppis, the large super-Earth is on a tight orbit which it can complete in nearly nine days.

HD 69830b was uncovered by a team of scientists led by veteran exoplanet hunter Christophe Lovis back in May 2006, using the European Southern Observatory's HARPS (High Accuracy Radial velocity Planet Searcher) spectrograph on the 3.6 metre La Sila telescope in the Atacama desert in Chile. The scientists also noticed that it is not alone around its star. Behind it in much more distant orbits are its larger companions, two collosal gas giants, HD 69830c and HD 69830d which weigh in at around 12 and nearly 19 Earth-masses respectively. It is thought that any world exceeding the mass limit of 10 Earth-masses enters a category of its own and just like HD 69830b, earn their class on the basis of their weights. Planets like HD 6980b are dubbed 'the super-Neptunes' due to their masses which are similar to our Solar System neighbour.

Due to its proximity to its star and the fact that it is out of its habitable zone - the distance from a star where it is possible for water to exist - chances of there being life on this super-Earth are really rather slim. But what if we were able to somehow move HD 69830b to a distance where conditions were just right? According to experts, super-Earths are not just scaled-up versions of their prototype, our planet, they're often presumed to be hostile worlds. Our home hosts a well defined core, mantle and crust, believed to have formed within its first 50 million years, through which heat is transported from the cooling core to the crust before bursting out into volcanoes. Additionally this convection of heat drives the plate tectonics that are crucial for recycling carbon and keeping an ideal climate. During their formation, super-Earths are not so lucky. Under the high temperatures and pressures within them, the viscosity of the rock, which the formation of a planetary core relies on, increases dramatically slowing the formation of the core, mantle and crust. And even if some internal structure formed within exoplanets like HD 69830b, the convection of heat would be slow. This would stop plate tectonics and minimise the volcanic activity which spews out the carbon dioxide that is so important for a planet to form an atmosphere and to keep it warm. Additionally, cooling of the core is reduced and the slowing of the dynamo effect snubs the presence of any water on the surface. The hostility continues as experts believe that the generation of a magnetic field is also out of the question, failing to hold onto any atmospheric water vapours as it is lost to space, and that's even if an atmosphere was able to be created in the first place. However, despite all of the doom and gloom, and obviously if HD 69830b could somehow move to a more comfortable position and have tectonic plates, large quantities of water found in the lithosphere could actually assist in engineering plate tectonics despite a weak heat flow in the interior.

Due to tidal heating within its interior, planet hunters believe that HD 69830b could throw out heat which would dwarf that outputted by Jupiter's volcanic moon, Io, by at least 20 times. Could this super-Earth harbour the jagged forms of volcanoes on its surface like Jupiter's companion or Venus? It is certainly possible but at the current time with current technology we unfortunately cannot say for sure.

Rocky world
A super-Earth is an exoplanet with a mass higher than Earth's but below the mass of a gas giant

"This rocky world is arguably the largest super-Earth yet discovered"

How are exoplanets located?

One way that scientists hunt down exoplanets is through a process known as the 'transit method'. This involves repeatedly measuring the brightness of many stars over a prolonged period. "What you're looking for are dips in a star's brightness caused by a planet orbiting it," says Don Pollacco, Project Scientist of SuperWASP (two robotic exoplanet hunting observatories that operate continuously all year). "As the planet moves in front of its star it blocks out a little light [and a dip in the host star's light curve is made]. The size of the dip in the light curve (also called the transit) tells you the size of the planet (relative to its star). Transiting planets are the jewels in the crown. The bigger the planet, the bigger the transit depth."

The transit method provides astronomers with lots of information, but there are limitations, as Pollacco admits. "[It] can only detect planets whose orbits are in our line of sight and as the probability of this is small, you need to look at a large number of stars," he says. "The other thing is that the further the planet is from its star the more exact the alignment has to be and hence the probability of it happening is lower." The transit method needs a helping hand from the radial velocity method on occasions. "The orbital inclination means we can use this with the doppler method to get the mass of the planet. This is the main quantity to compare against theoretical models of planets."

2 Largest gas giant

HAT-P-32b

Size: 2.037 Jupiter-radii
Distance from Earth: 1,044 light years
Type: Gas giant
Most like: Jupiter

Narrowly missing the title of the biggest gas giant as it has yet to be confirmed if it is indeed a planet and not a brown dwarf, CT Cha b is pipped to the post by HAT-P-32b. This hot Jupiter, which almost weighs the same as its prototype at 94% of its mass, might not be the heaviest gas giant on the block but it is certainly the largest, swelling to a size twice that of our Solar System's giant.

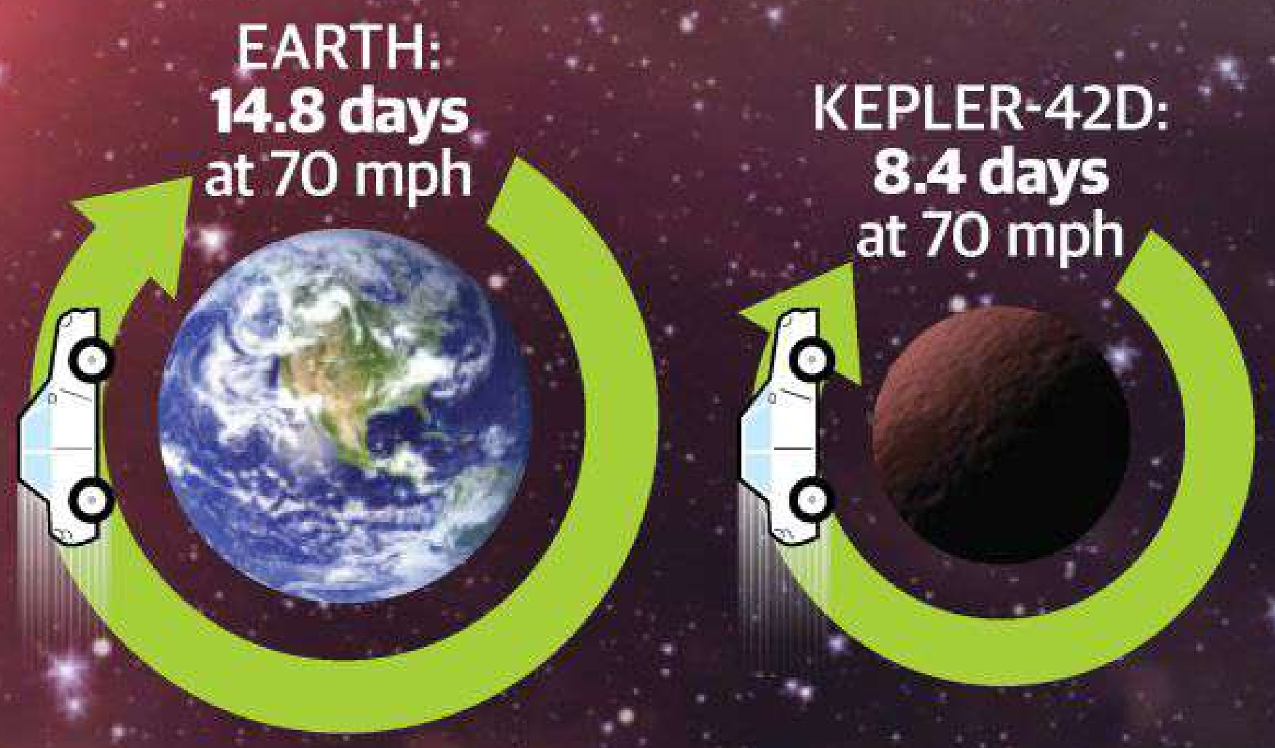
Orbiting its Sun-like or F-type star in the constellation of Andromeda on a slightly elliptical orbit, HAT-P-32b rests some 1,044 light years away from Earth and was uncovered with the help of the six-telescope HATNet Project, an organisation in search of planets passing across their parent stars. While the team of astronomers that scrutinised HAT-P-32's data were sure that they had hit on the existence of a great gas giant, confirming it proved to be tricky with high levels of jitter dominating the measurements and scuppering any chances of certainty in finding an exoplanet around the star.

It was not until spectra collected using the High Resolution Echelle Spectrometer (HIRES) at WM Keck Observatory in Hawaii could astronomers lock down the radial velocity of HAT-P-32, later concluding that the shake of what they assumed was the presence of an undiscovered planet, was in fact rambunctious stellar activity.

Determined not to give up on the existence of the then elusive HAT-P-32b, astronomers employed the KeplerCam CCD instrument at the Keck observatories to snap photometric observations, constructing the light curve which would soon reveal the shy gas giant as it passed across its star with the help of extensive analysis using the Blendanal program.

Although some might argue that HAT-P-32's jitter could be the result of a dimmer secondary companion tangoing with the star in a binary, the existence of a planet around the metal-poor star was confirmed. While HAT-P-32 might be younger than our Sun at an age of 3.8 billion years, it is also larger, heftier and hotter, emitting nearly three times the amount of energy our star does.

How long will it take to drive around Kepler-42d?



"It has a radius just 0.57 times that of Earth, making it about the same size as Mars"

3 The smallest

Kepler-42d

Size: 0.57 Earth-radii
Distance from Earth: 126 light years
Type: Terrestrial
Most like: Mars

For many years searches for exoplanets were dominated by giant hot Jupiters. Where were the small planets? In recent years this has changed as astronomers' detection techniques have become more sensitive to smaller planets and the smallest one discovered so far is Kepler-42d.

This midget world lives around a red dwarf 126 light years away, revealing itself to astronomers through the tiny dip in light it causes in its parent star as the planet moves in front of it. It has a radius just 0.57 times that of Earth, making it about the same size as Mars. Kepler-42d's mass is just less than Earth's at 0.9 Earth masses.

Red dwarf stars are cool, miniature stars and their attendant planetary systems are similarly scaled down. Kepler-42d is the outermost planet of three known in orbit around their star, and yet it is still so close to its star that its year lasts just less than two Earth days. At this proximity Kepler-42d has a surface temperature of at least 181 degrees Celcius, assuming no atmosphere. This is far too hot for life as we know it.

However, discovering rocky planets of any type is important because it helps tell us that planets the size of Earth or smaller are common in the universe. Smaller, rocky planets have the best chance of being habitable, provided they live in their star's habitable zone and they have an atmosphere and water.

4 The most ancient

HIP 11952b

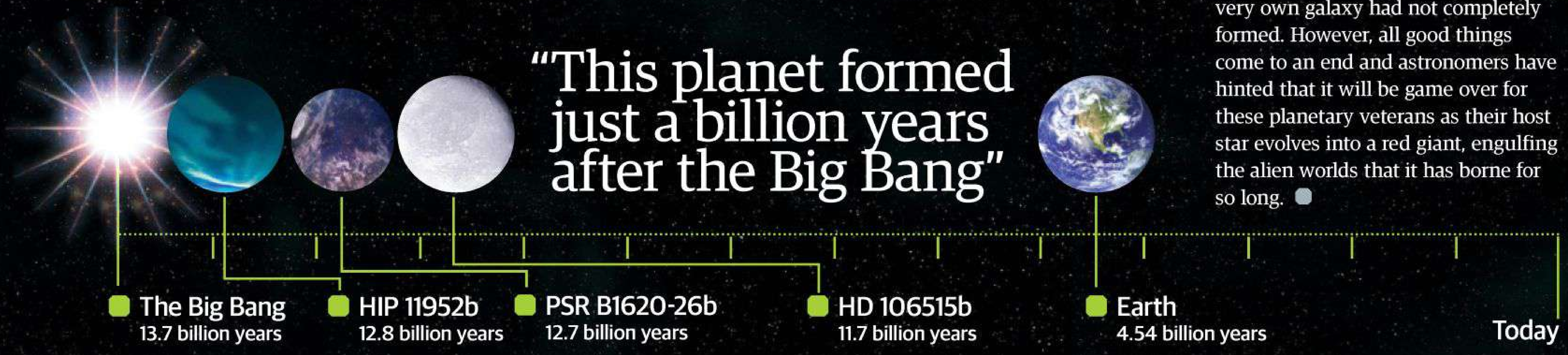
Size: 2.93 Jupiter masses
Distance from Earth: 375 light years
Type: Gas giant
Most like: Jupiter

Until last year, the oldest world that we knew of was PSR B1620-26b – a distant world orbiting the pulsar, PSR B1620-26. A pulsar is actually a neutron star, an incredibly dense relic of a star's core, just a few dozen kilometres across in size. Nobody expected to find any planets around them but in the early 1990s several were found, their gravity causing slight delays in the regular tick-tock-tick-tock of a pulsar's radio pulses. PSR B1620-26b, which is also in the same system as a white dwarf, was one of these exoplanets.

However in early 2012, the title of the oldest exoplanet known was snatched by not one, but two alien worlds right on our star's doorstep at a short distance of 375 light years away. Uncovered with the help of radial velocity, the duo dubbed HIP 11952b and HIP 11952c are gas giants orbiting a Sun-like star, with the hefty HIP 11952b completing its tango around its star in nine and a half months while its lighter companion whips around in a short seven days.

At an ancient 12.8 billion years, these gas giants are believed to have formed at the dawn of the universe, less than a billion years after the Big Bang and at a time where our very own galaxy had not completely formed. However, all good things come to an end and astronomers have hinted that it will be game over for these planetary veterans as their host star evolves into a red giant, engulfing the alien worlds that it has borne for so long.

"This planet formed just a billion years after the Big Bang"



5 Closest to our Sun

Alpha Centauri Bb

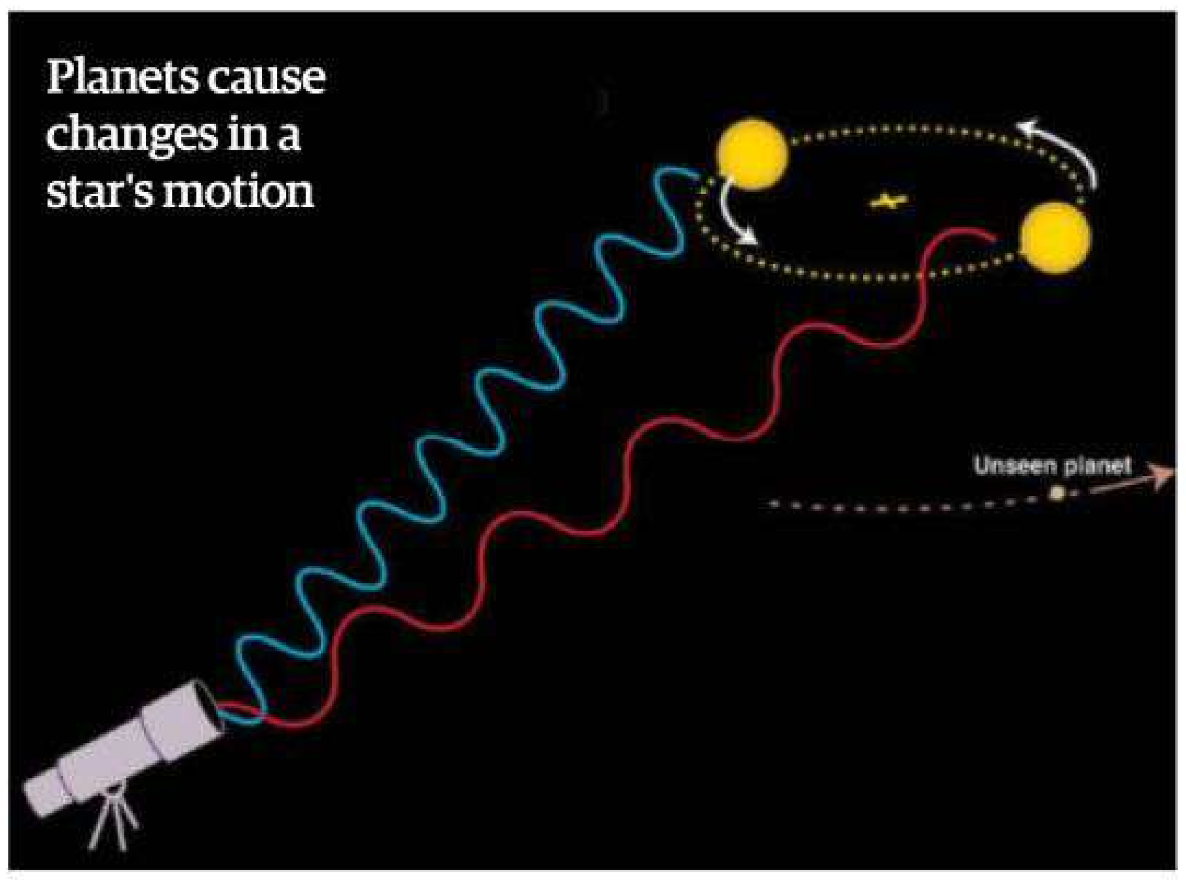
Size: Unknown
Distance from Earth: 4.3 light years
Type: Terrestrial
Most like: Venus

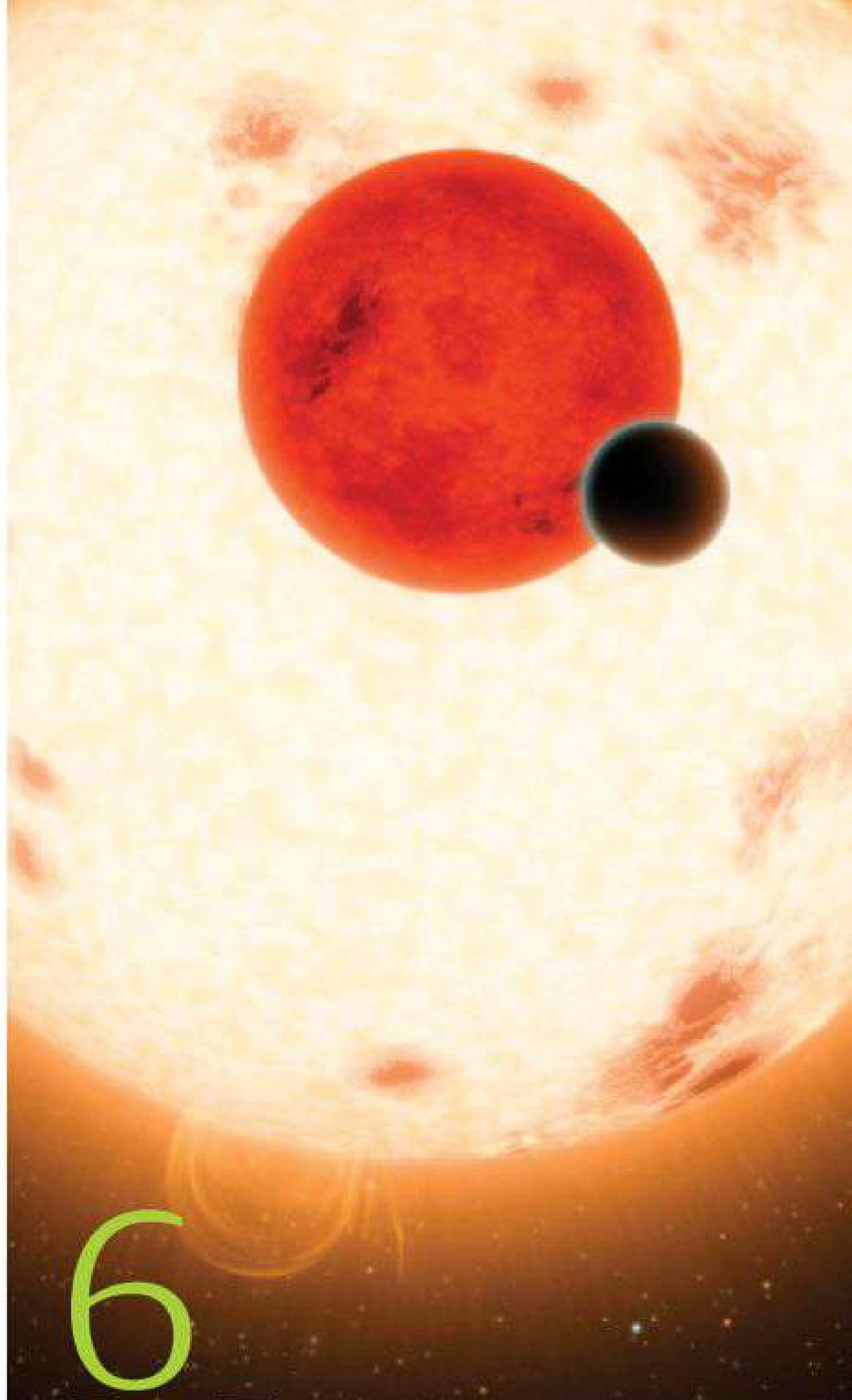
Everyone was looking for planets around our stellar neighbours, the trio of stars in the Alpha Centauri system, 4.3 light years away. Then in October 2012 astronomers found one using the radial velocity method, a rocky planet with a mass of around 1.13 times that of Earth. Unfortunately the planet is very close to its star, Alpha Centauri B, meaning its rocky surface is probably molten with temperatures of 1,220 degrees Celsius. However, astronomers are finding that where there is one rocky planet, there is usually more, so it's possible there are other planets orbiting Alpha Centauri B. Because Alpha Centauri is the closest star system to us, one day we may be able to send probes, such as Project Icarus, to explore the planets there. And if there was life on any so far undiscovered planets, having a conversation wouldn't be too bad - after sending a message we'd only have to wait 8.6 years for a reply!

Discovering planets via radial velocity

The radial velocity method is currently the most popular way to track down distant worlds. "If planets are orbiting a star, the spectral lines undergo small redshifts and blueshifts (the Doppler effect) as the star 'wobbles' around the system's mutual centre of gravity," says Mikko Tuomi from the University of Hertfordshire who was a co-discoverer of HD 40307g. "[With this] we can obtain information on the orbits of the planets, though only lower limits for the masses because we cannot determine the orientations of the orbits in space," says Tuomi.

"Unlike the transit method, the radial velocity method enables detections of planets around all nearby stars. The transit method is based on occultations and their probability for any given system is roughly 1% so the radial velocity method enables the detections of 100 times more planets."





6 Most suns

Kepler-64b

Size: 20-50 Earth masses
Distance from Earth: 5,000 light years
Type: Gas giant
Most like: Neptune

Also dubbed Planet Hunters 1, Kepler-64b belongs to a two-gigayear-old quadruple star system called Kepler-64. The giant Neptune-sized world, which weighs between 8% and 14% the mass of Jupiter and has a radius of just over six times that of the Earth's, orbits the closest binary to us in a circumbinary orbit.

It has a backdrop of a more distant binary system orbiting at around 900 times the distance between the Sun and the Earth. Kepler-64b's closest binary, with its orbital period of 20 days, comprises of a 1.5 solar mass whitish coloured F-type dwarf and a 0.41 solar mass red M-type dwarf which are separated at 100 AUs from each other.

It takes roughly 138 days for the gas giant to complete one orbit. The remaining pair are separated by 60 AU and contain a star equivalent to our Sun at a mass of 0.99 solar masses, which is accompanied by a lighter red dwarf companion just over half the mass of our Sun.

Holding the title of the first ever quadruple star system to be found, this exoplanet was uncovered by two amateur astronomers from the project Planet Hunters.

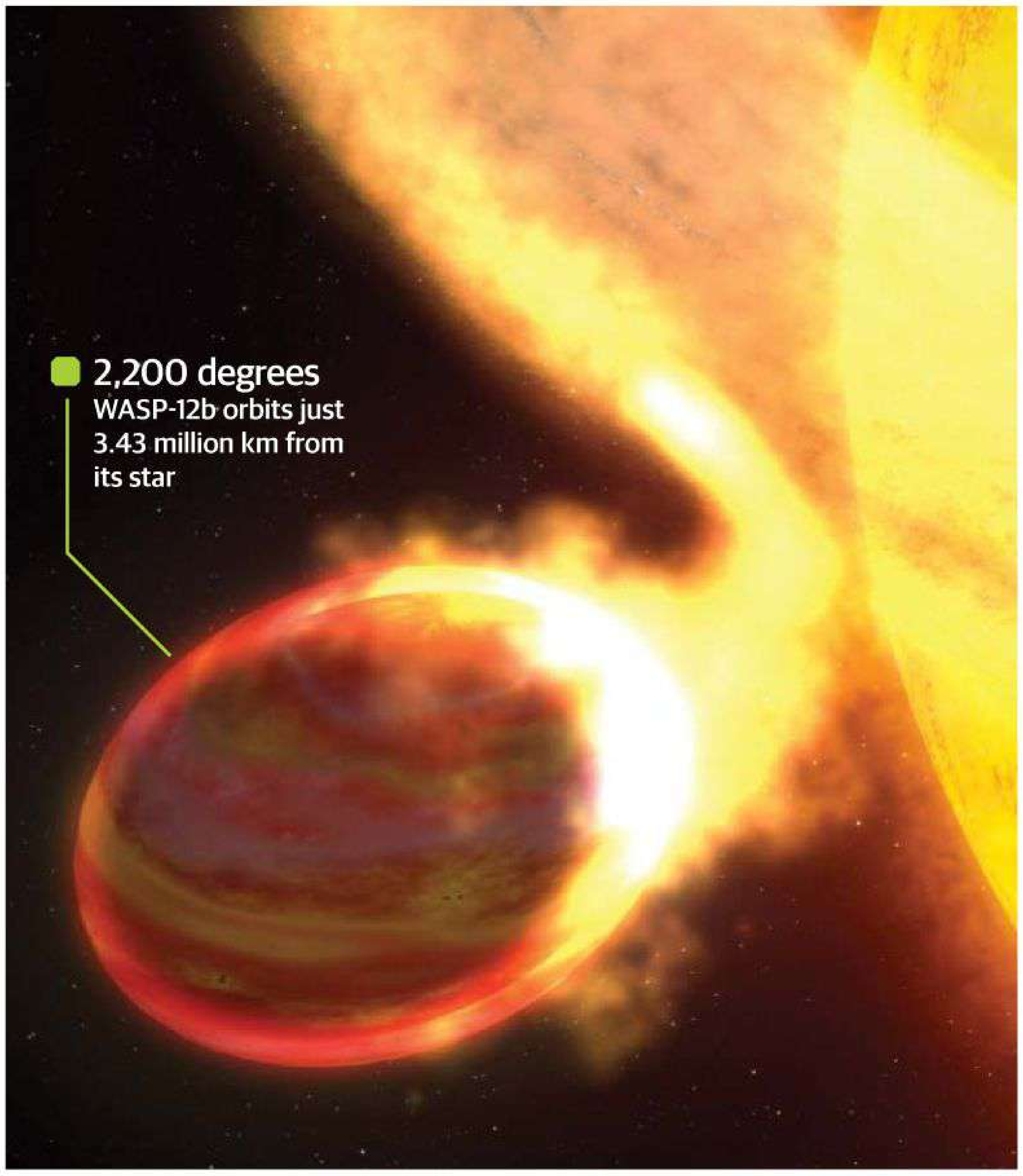
7 Hottest

WASP-12b

Size: 1.73 Jupiter-radii
Distance from Earth: 1,394 light years
Type: Gas giant
Most like: Jupiter

It's an amazing fact that the hottest planet found so far was discovered using camera lenses bought from eBay! That's how a group of British universities were able to afford to set up SuperWASP (Wide Angle Search for Planets), a collection of cameras based in both La Palma in the Canary Islands and in South Africa.

WASP-12b is so hot (2,200 degrees Celsius) because it orbits incredibly close to its star, at just 3.43 million kilometres. This is 1/44 of the distance between Earth and the Sun. It's so close to its star that the planet is being stretched by the star's gravity and gaseous material from its atmosphere is ripped away into space to be consumed by the star – it is eating the planet alive! As the star's gravity flexes WASP-12b in this deadly relationship, it causes something called tidal heating inside the planet, contributing to its scorching temperature along with its sheer closeness to its star.



2,200 degrees
WASP-12b orbits just 3.43 million km from its star

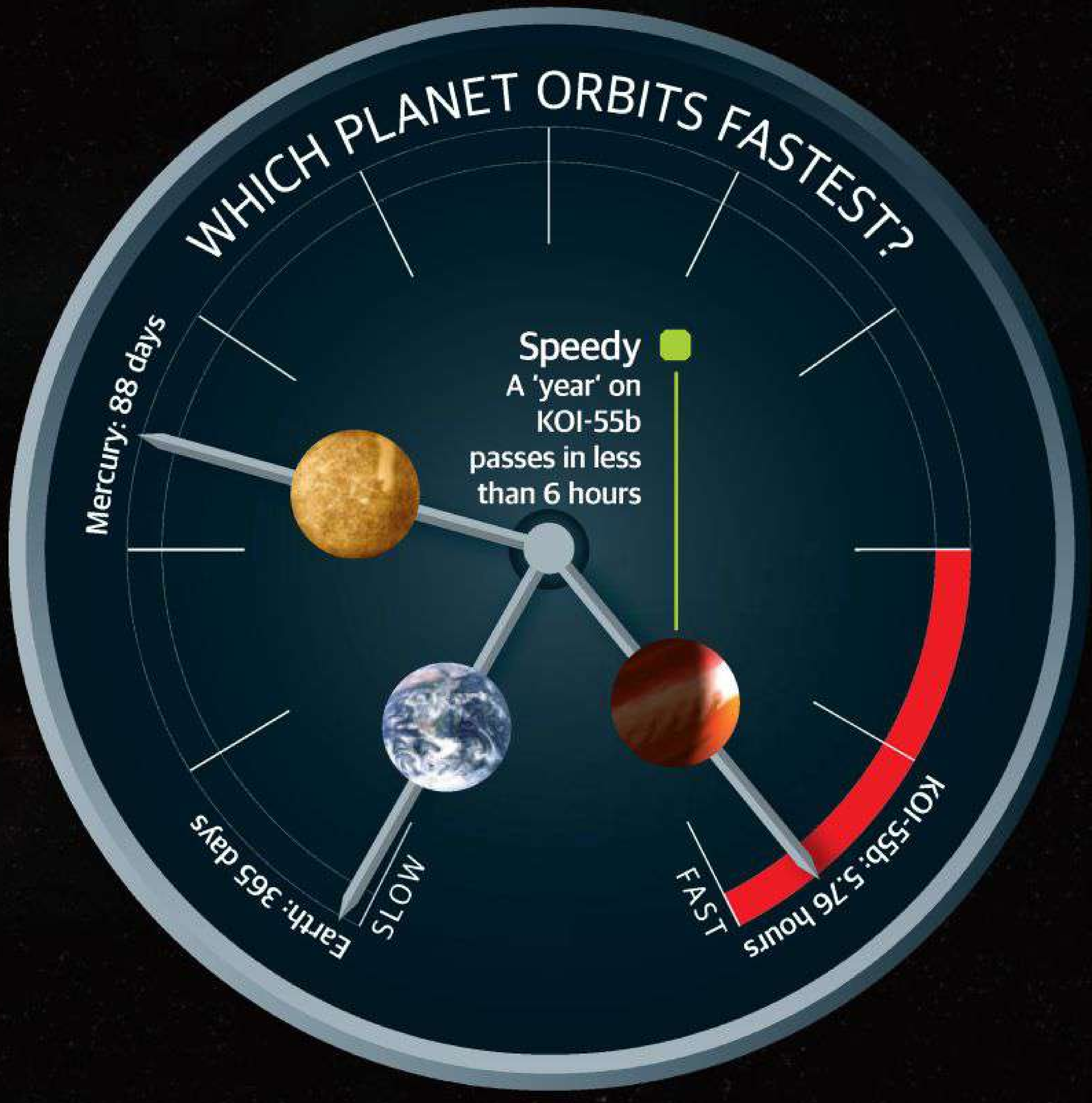
8 Fastest

KOI-55b

Size: 0.068 Jupiter-radii
Distance from Earth: 3,349 light years
Type: Terrestrial
Most like: NA

The nippiest exoplanet is none other than KOI-55b, which completes an orbit around its parent star KOI-55 in a record-breaking time of just 5.76 hours. KOI-55b's star is a subdwarf B star which passed through the red giant stage approximately 18.4 million years ago. When it finishes the helium that it is currently fusing it will contract and evolve into the next stage of its life – the white dwarf – with a radius of around 0.2 times that is the Sun.

Detected by the reflection of their star's light on their surfaces, KOI-55b and its companion KOI-55.02, are believed to have been gas giants back in their day which spiralled inward toward KOI-55 where they were stripped of their bulk, leaving their rocky cores behind. These now orbit the subdwarf star with KOI-55b a fraction of the mass of Jupiter at 0.14 Jupiter masses.



Speedy
A 'year' on KOI-55b passes in less than 6 hours

The telescopes

Kepler
Launched March 2009 by NASA from Cape Canaveral inside a Delta II vehicle, Kepler is a space observatory on a mission to discover planets just like Earth. The exoplanet hunter monitors the brightness of over 140,000 main sequence stars and analyses for exoplanetary transits. During its short time in operation, the spacecraft has found over 2,300 planet candidates, 105 of which have been confirmed as super-Earths and hot Jupiters.

Spitzer
Approximately 167,690,000 kilometers from us, the Spitzer Space Telescope is a cryogenically-cooled infrared observatory. Its aim is to study stars, planets, galaxies, black holes, giant molecular clouds and extrasolar planets. The NASA telescope has to be hot and cold, with equipment needing to operate close to room temperature and an onboard tank of liquid helium keeping the telescope's Cryogenic Telescope Assembly cooled to around -268 degrees Celsius.

9 Most likely to support life

HD 40307g

Size: 7 Earth masses
Distance from Earth: 42 light years
Type: Terrestrial
Most like: Earth

Originally thought to host just three planets, HD 40307 was recently discovered to be smuggling three more distant worlds – one of which might be Earth's over-sized twin. Among the six exoplanets that orbit their 42 light year distant star which rests in the Southern hemisphere constellation Pictor, this super-Earth, named HD 40307g, circles in the habitable zone bathed in HD 40307's orange light. It is thought conditions could just be right for the existence of liquid water and possibly a stable atmosphere.

The recent finding, as covered in the last issue of **All About Space**, was captured via radial velocity at the European Southern Observatory's HARPS apparatus, by a team of astronomers led by the University of Hertfordshire's Mikko Tuomi and Guillem Anglada-Escude from the University of Goettingen in Germany. The team of researchers believe that, while the five other exoplanets which tightly orbit HD 40307 would be too hot to support life as we know it, there really is something special about 40307g that has led astronomers to believe that, right now, it is the closest we have come to finding the fabled "Earth 2.0". Not only does the world hang out in the habitable zone of its star, but it's suggested that it may be rotating on its axis and as it twirls, creates an Earth-like environment with days leading into nights.

Unfortunately, we have to wait for the next generation of large telescopes to find out if this is a friendly place to live or not, but in the meantime, and according to models, HD 40307g has been pinpointed as the most likely exoplanet where life could have a chance of residing.

10 Newest discovery

omi CrB b

Size: 1.5 Jupiter masses
Distance from Earth: 270 light years
Type: Gas giant
Most like: Jupiter

Detected with the help of radial velocity, omi CrB b is the most recent exoplanet discovered. With a mass of 1.5 Jupiter masses, this new kid on the block is very likely to be a gas giant. At a distance of over 270 light years away, omi CrB b leads a lonely existence and is currently the only planet that we know of orbiting its variable orange giant star which rests in the constellation Corona Borealis, taking some 187 days to complete one orbit.

omi CrB b is a gas giant at 270 light years away from us

5 AMAZING FACTS ABOUT

Carbon worlds

Their volcanoes spout diamonds

Carbon exoplanets could sport a thick layer of diamond under a topping of carbon in the form of the mineral, graphite, which can be found in the lead of pencils. Diamonds might also erupt from volcanoes on the surface of carbon planets, spitting out mountains of these jewels.

They are heavily polluted

If a carbon world is cool enough – at about 77°C (170°F) – a cycle would be kick-started where rain, made of organic materials, would fall onto the surface from an atmosphere of carbon dioxide or carbon monoxide and other gases. Such a combination would cause their skies to be thick with smog.

We may have found two already

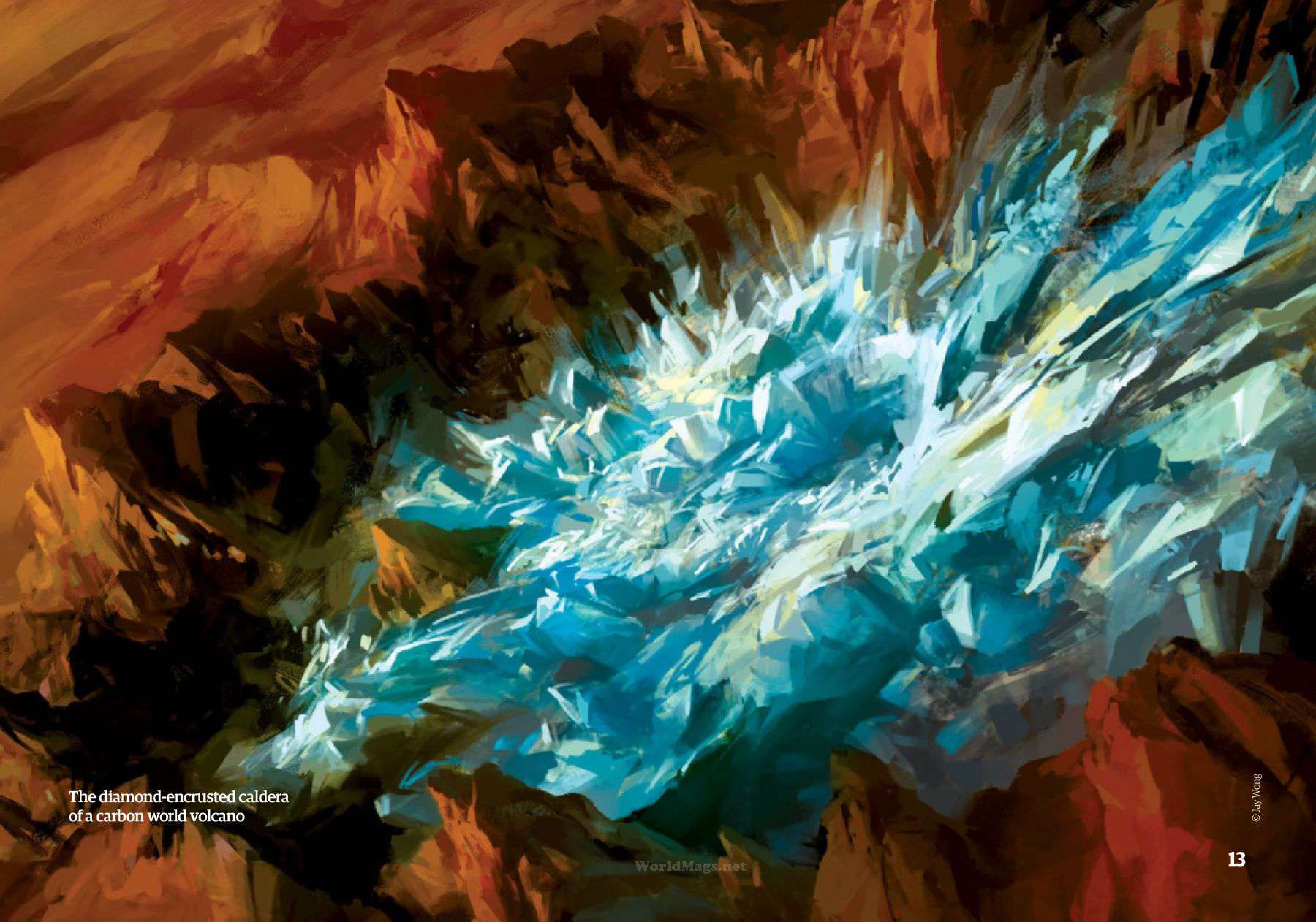
We think that there are at least two possibilities of carbon worlds out of the exoplanets we have detected so far. One could be around pulsar PSR 1257+12, forming from the disruption of a star churning out carbon. Another might be the planet we know as 55 Cancri e.

They're devoid of water

Comets and asteroids are likely to have delivered water to our planet early in the Solar System's history; beginning their journey far beyond Earth, way past a boundary known as the snow-line before smashing into its surface and depositing their water, previously locked up as ice. On carbon worlds the abundant carbon of developing star systems snags oxygen and stops water forming.

More are made every day

These worlds are probably found close to the core of our galaxy or in the globular clusters found orbiting it – places where you're most likely to find old stars. When these ancient stars pass on, they spew out gigantic amounts of carbon and go on to create these unusual planets. All stars must end, so it makes sense that, as more generations are snuffed out, we will find more carbon worlds.



The diamond-encrusted caldera of a carbon world volcano

© Jay Wong

HOW PLANETS FORM

Written by Tom Harris

Discover how our home, along with our Solar System neighbours and every other planet in the universe, was born from a chaotic cloud of dust and gas

In a sense, planetary birth is a side effect of a larger birth: the formation of a star. Stars form from nebulas, massive clouds of gas and dust dominated by hydrogen and helium. Now and then, a disturbance in a nebula concentrates an area of gas and dust into a denser knot of material. If the knot is big enough and dense enough, it will exert enough gravitational pull to collapse in on itself. The huge volume of super-dense gas concentrates at the knot's centre, and the gravitational energy heats it up to form a protostar. With sufficient mass, the energy of the protostar increases, eventually initiating a nuclear fusion reaction and graduating to a proper star.

Meanwhile, according to the solar nebula theory, surrounding gas and dust form a protoplanetary disc, or proplyd, around the protostar. When the protostar first begins to form, the surrounding material is still an unordered, slowly churning cloud. But the protostar's growing gravitational pull accelerates the cloud's movement, causing it to swirl around the centre. As the swirling mass speeds up, it flattens out, forming a thin disc, packed with all the material that will eventually coalesce into planets.

As well as explaining how planets form, the solar nebula theory also explains why solar systems take the form they do. The planets all revolve in the same direction around a central star, in the same plane, because that's how the material disc originally swirled around the protostar.

Exactly how it all comes about is still up for debate, and there may actually be many different planet formation processes. The prevailing understanding, called the accretion model, is that planet formation begins when individual bits of matter in the disc clump together into bigger chunks. The accretion model seems to be correct at least in the case of rocky terrestrial planets, like Earth and Mars, which form from silicates and heavier metal, such as iron and nickel.

Astronomers generally agree that a planet like ours begins with an invisible piece of dust. Microscopic grains in the disc grow by condensation, the same process behind snowflake formation. In condensation, individual heavy gas atoms or molecules stick to a grain, rapidly expanding its size into a more substantial solid particle.

When the particles are very small and light, turbulent gas motions stir them up, swirling them outside the flat plane of the proplyd. But when they reach sufficient mass they're heavy enough to settle into the relatively thin rotating disc. In the crowded disc, particles collide more frequently, speeding up the growth of larger and larger chunks.

At about the point a chunk of solid matter grows to a kilometre across, it graduates to a planetesimal. A planetesimal is massive enough that its gravitational pull attracts smaller chunks of matter, accelerating the rate of growth. The result is a relatively small number of planetesimals steadily capturing the smaller chunks and particles in the disc.

When a terrestrial planetesimal grows large enough, the energy of

many collisions along with radioactive material it's accreted heat everything to melting point. As a melted mass, the planetesimal's structure can reform. In a process called differentiation, the force of gravity concentrates the melted metals into an inner core, surrounded by an outer crust of lighter rocky silicates. The result is a protoplanet, an asteroid-like mass with distinct layers. Over time, gravity evens out the protoplanet's shape, forming it into a sphere.

A terrestrial planet might form an atmosphere layer through outgassing. Essentially, heat from the planet's interior core unlocks gases trapped in the planet's solid and molten interior. Planets might then add to this atmosphere through encounters with other solar system bodies.

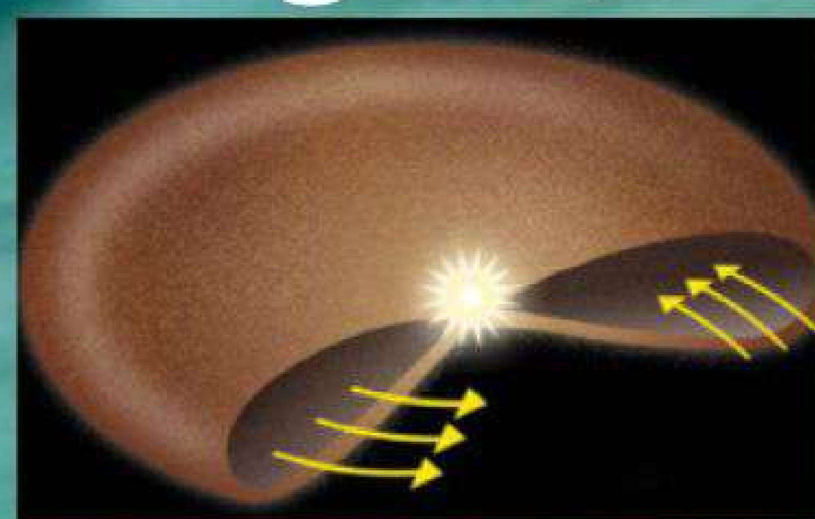
As the diversity of our own Solar System demonstrates, atmospheres vary a great deal. Any particular atmospheric recipe requires not only the right mix of planetary matter, but also a precise balance of planetary size and proximity to the central star. When a smaller planet orbits very close to a star, like Mercury, the sun's heat blasts away any atmosphere, leaving a barren rock. Meanwhile, a planet like Mars is so far from the Sun that all its water is locked up in ice. But just a bit further in, you get Earth – a planet that's the right size and in the right position to form a robust atmosphere that could support life.

While there is general agreement among astronomers that terrestrial planets formed along these lines, the origins of Jovian gas giant planets, like Jupiter and Saturn, are less certain. One possibility is they start out the same basic way as terrestrial planets, steadily accreting solid matter to form a massive protoplanet. If it grows large enough – about 15 times the size of Earth – such a protoplanet exerts a strong enough gravitational pull to capture hydrogen and helium gas in the proplyd. The gaseous mass then sweeps up more material, growing into a Jovian behemoth.

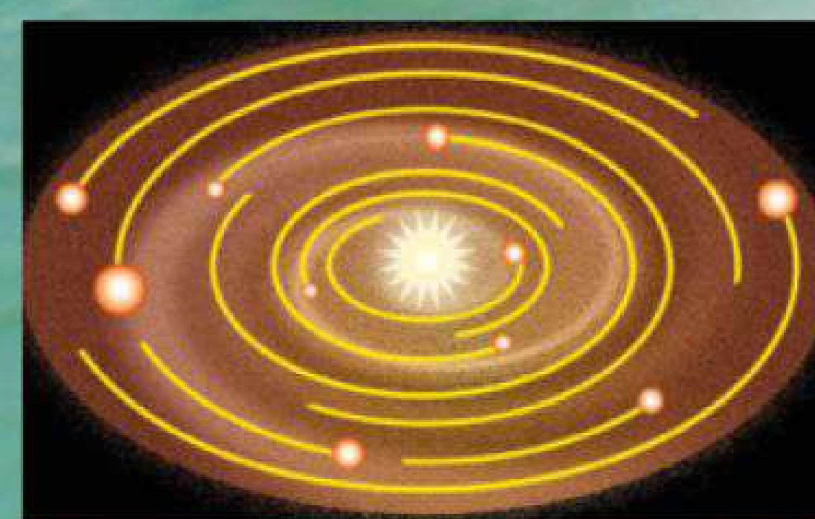
There is a relatively small supply of heavy metals and silicate in a proplyd, making it unlikely that a protoplanet could accumulate enough metal and rocky material to reach the size necessary to hold on to hydrogen and helium gas. Instead, this model says, the initial planetary core of a Jovian planet forms out of frozen hydrogen compounds, such as methane, ammonia and water. Near the centre of a proplyd, the developing protostar makes it too hot for hydrogen

Origins of a solar system

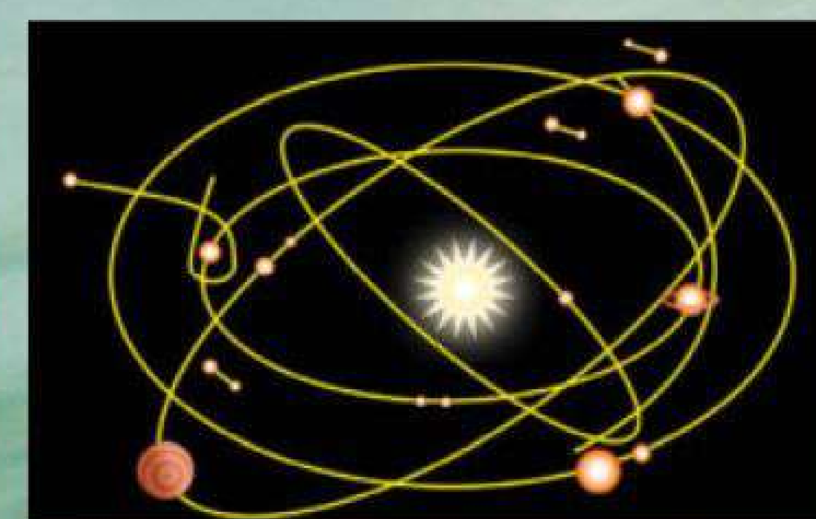
Gas giant, the accretion model



1. Dirty snowballs
Dust grains and bits of frozen hydrogen compounds condense and then collide and stick together, forming bigger and bigger icy planetesimals.

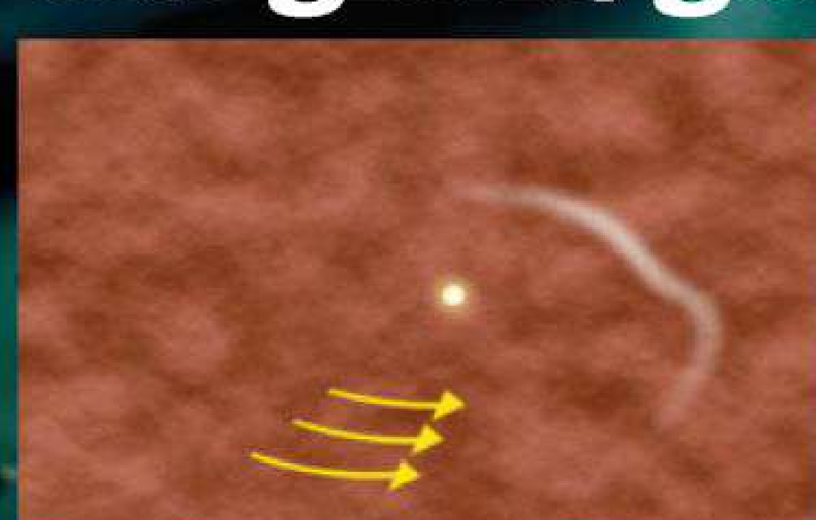


2. Capturing gas
Some planetesimals grow so big that their gravitational pull captures hydrogen and helium gas in the protoplanetary disc.



3. Too big to fail
The gas giants grab a huge supply of the disc's hydrogen and helium gas. Their massive gravity pulls in or scatters remaining planetesimals.

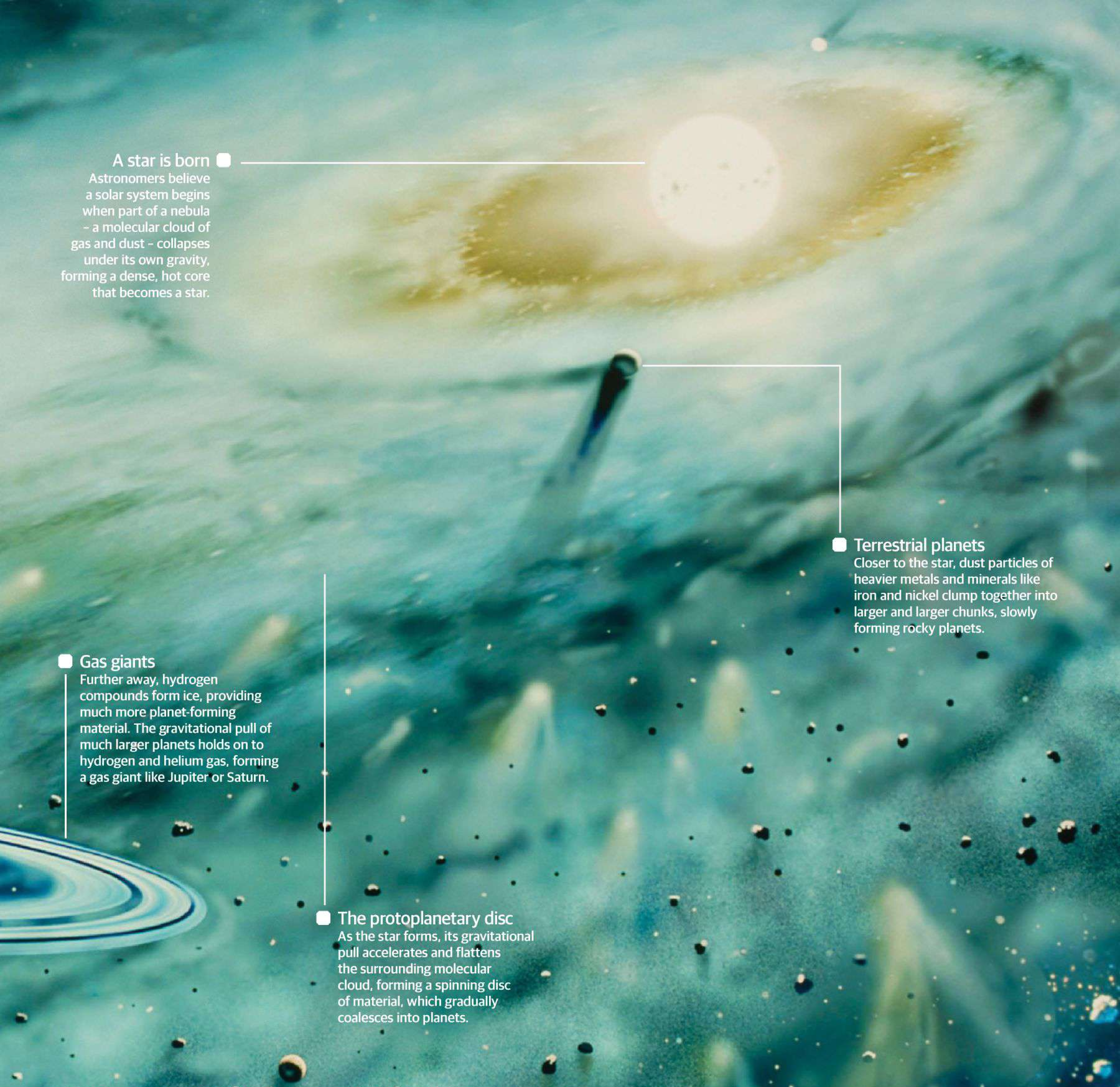
Gas giant, gas collapse model



1. Concentrations in the disc
In the disc of gas and dust that forms around a protostar, the dynamics of the rotation cause uneven distribution of hydrogen and helium gas.

2. 'Instant' planet
A clump of dense gas collapses under its own gravity to form a gaseous planet. The new planet picks up dust and ice, which collect into a solid core.

3. Glutton for gas
As the planet makes its way around the disc, its strong gravitational pull sweeps up more gas, making it bigger and bigger.



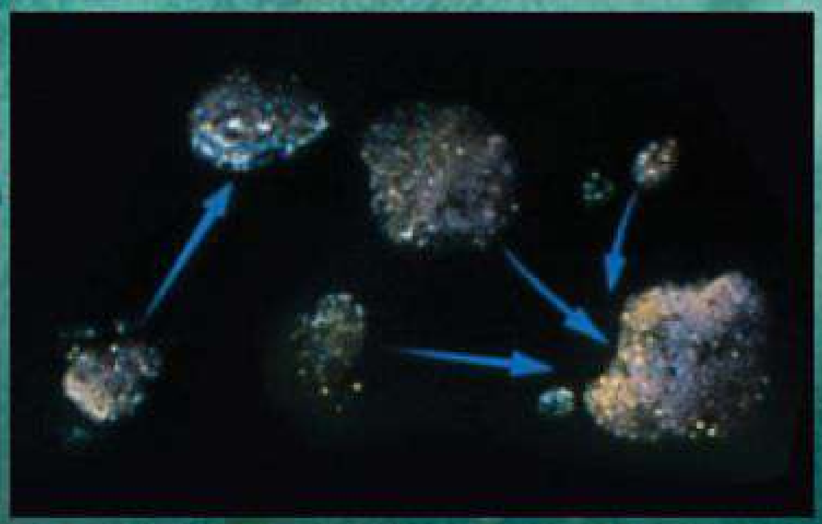
A star is born
Astronomers believe a solar system begins when part of a nebula – a molecular cloud of gas and dust – collapses under its own gravity, forming a dense, hot core that becomes a star.

Terrestrial planets
Closer to the star, dust particles of heavier metals and minerals like iron and nickel clump together into larger and larger chunks, slowly forming rocky planets.

Gas giants
Further away, hydrogen compounds form ice, providing much more planet-forming material. The gravitational pull of much larger planets holds on to hydrogen and helium gas, forming a gas giant like Jupiter or Saturn.

The protoplanetary disc
As the star forms, its gravitational pull accelerates and flattens the surrounding molecular cloud, forming a spinning disc of material, which gradually coalesces into planets.

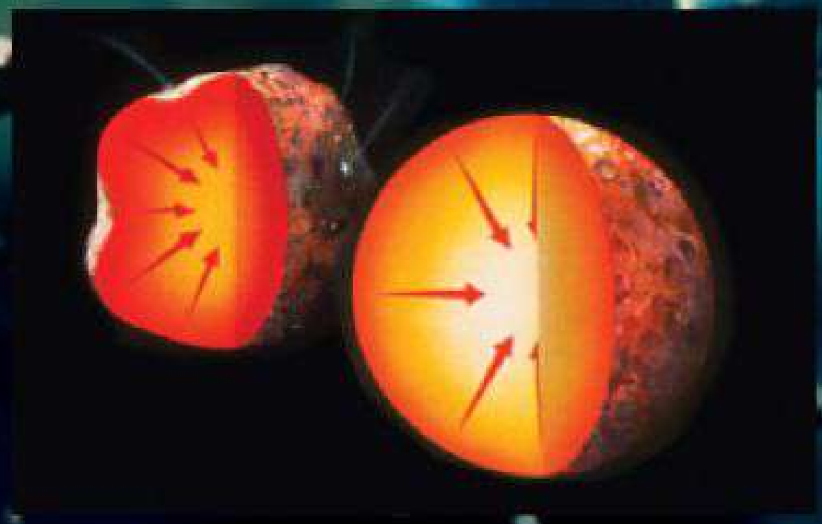
A terrestrial world is born



1. Let's stick together
Mineral and metal dust particles throughout the molecular cloud collide and clump together, forming larger rocky particles.

2. Running with the crowd
As trillions of these particles rotate around the developing star, they're constantly colliding, forming bigger asteroid-like pieces through accretion.

3. Forming a planetesimal
When a rocky chunk grows to about 1km across, its gravitational pull is able to attract other pieces, speeding up the accretion process.



4. Graduating to a protoplanet
Intense heat melts the rocky material. During melting, elements like iron and nickel concentrate at the centre of the planet, giving it distinct layers.

compounds to condense into frozen solids. They remain in gaseous form and so do not accrete to developing planetesimals. But if you move far enough away from the hot protostar, past what's called the frost line, the temperature drops low enough that hydrogen compounds can freeze. With a much more abundant supply of solid material, large icy protoplanets can form and capture the swirling hydrogen and helium gas.

The organisation of our Solar System supports this theory. The inner planets, Mercury, Venus, Earth and Mars are all relatively small and rocky, suggesting forming giant icy or gaseous planets wasn't possible close to the Sun, while the outer planets, Jupiter, Saturn, Uranus and Neptune, are much larger.

The chief argument against the accretion model for Jovian planets is timing. In well-supported models of solar system evolution, there simply isn't enough time to grow the massive icy cores before the developing solar system loses the bulk of its hydrogen and helium gas supply. While the lighter gases are the dominant material during the proplyd's early life, their days are numbered. In the case of our own Solar System, some 10 million years after the Sun first formed as a protostar, the energy of nuclear fusion reactions likely produced powerful solar winds that would have cleared out the remaining gas in the proplyd. That's a tight window for Jovian gas giants to form.

And neighbouring stars may lead to the window shrinking even further. Astronomers believe that stars generally form in clusters that contain massive, hot stars. Calculations say radiation from these stars would accelerate the evaporation of gaseous material in nearby proplyds, shrinking the period of plentiful hydrogen and helium to between 100,000 and 1 million years. That doesn't appear to be enough time for a Jovian gas giant to form through the accretion model, yet observations of distant solar systems show that these gas giants are very common.

An alternative theory, known as the gas collapse model, presents a faster formation scenario. According to this model, gas giants form directly from the swirling hydrogen and helium in a developing proplyd. As the material revolves around the protostar, turbulence in the disc distributes it unevenly. This unevenness forms knots of dense gas. When enough gas is concentrated tightly enough, its dense mass causes it to collapse in on itself, forming a giant gas ball. To put it another way, the gas giant is like a failed star. It forms the same basic way as the protostar, but doesn't have sufficient mass and energy for a nuclear fusion reaction.

The embryonic planet's gravitational pull takes over from there, sweeping up massive amounts of gas, as well as any solids in the vicinity, quickly adding to its bulk. Collected ice and metals condense at the planet's centre, forming a solid core after the gas has accumulated, rather than before. The whole process might happen as quickly as a few hundred years.

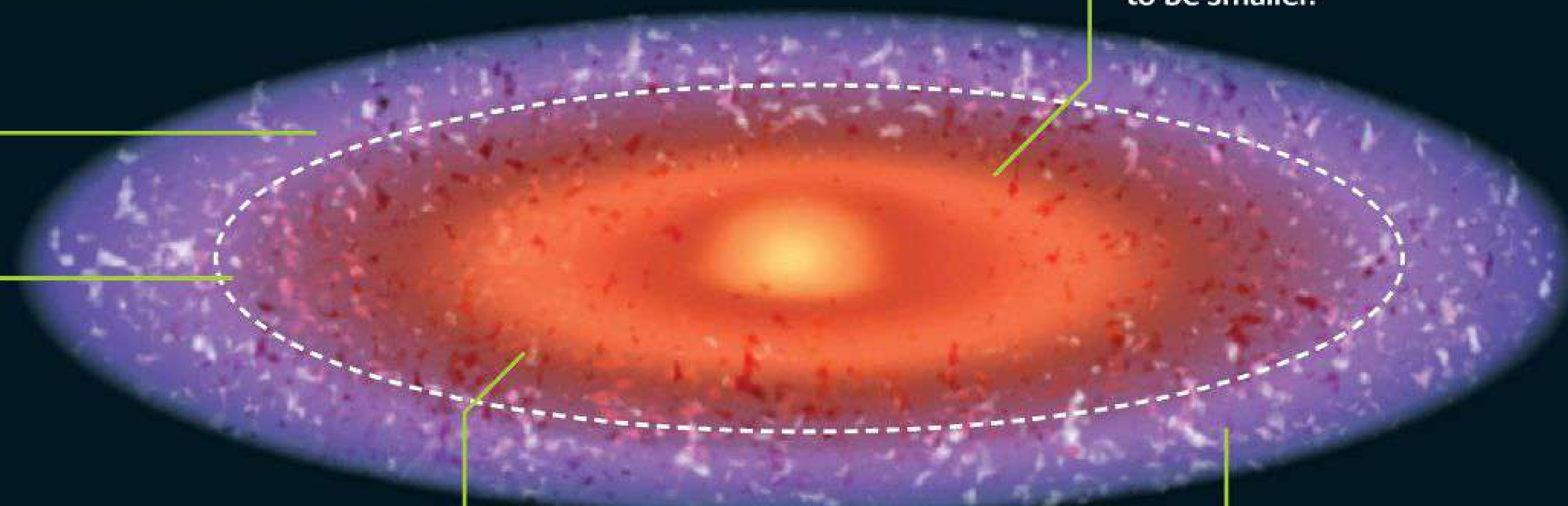
Observations of Jovian exoplanets (planets located outside our Solar System) have given some credence to this model - or at least challenged the Jovian accretion model. In the wave of exoplanet discoveries over the past 25 years, one of the biggest surprises has been the so-called 'hot Jupiters', Jovian gas giants that orbit very close to their suns. These planets would seem to contradict the notion that gas giants only form beyond the frost line. However, they may have formed further out, but then migrated towards their suns.

A host of exoplanet discoveries have given astronomers a much bigger picture of the range of possible planets, which has yielded new clues about how planets might form. But examining the end results can only tell them so much. Fortunately, we're likely entering a new era of direct proplyd observation, thanks to advances in telescopic technology. The new Atacama Large Millimeter/submillimeter Array (ALMA) radio telescope in Chile, which should be fully operational in March, has already yielded unprecedented images of planet formation in progress. As new discoveries follow, astronomers expect to fill in more pieces of the puzzle, taking us ever closer to understanding how our planet, and by extension all of us, came to be.

The frost line explained

Mainly gas
A protoplanetary disc is primarily made up of hydrogen, helium and various hydrogen compounds, such as water and ammonia.

Hot and rocky
Closer to the centre of a protoplanetary disc, the developing star makes it too hot for gases to freeze into a solid. Forming from a limited supply of metals and rocky material, inner planets tend to be smaller.



The frost line
The frost line marks the distance from the star where temperatures drop low enough for hydrogen compounds to freeze.

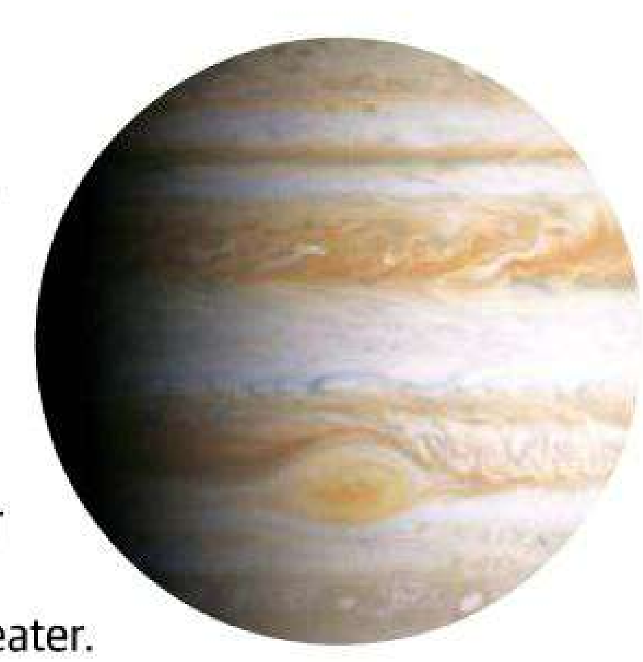
Hydrogen and helium gas
Hydrogen and helium gas exists throughout the protoplanetary disc, but temperatures never drop low enough for it to solidify. Only immense gravitational pull can condense it into a planet.

Icy planets
Beyond the frost line, gaseous hydrogen compounds like methane and ammonia condense into icy solids, which may form planetesimals.

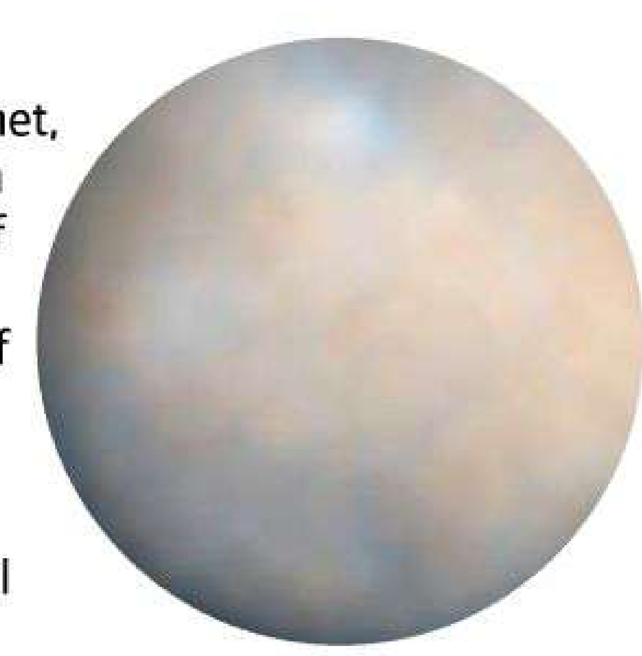
Types of planets

Terrestrial
Terrestrial planets like Earth and Mars are rocky planets with metal cores and high densities. They are smaller than gas giants and have slower rotation periods. In addition, their smaller size means they are less likely to have moons.

Gas giant
At a further distance from their orbiting star, gas giants are able to accrete more matter in their formation, giving them a large size and mass. For example, Jupiter is 11 times larger than Earth, and has a volume 1,300 times greater.



Dwarf planet
Smaller than a true planet, the difference between an asteroid and a dwarf planet comes down to its shape. To be a dwarf planet, a body must have sufficient mass to achieve hydrostatic equilibrium, when it will become spherical.



Planet formation in action

Our nearest star-forming region is the Orion Nebula, a massive cloud of gas and dust around 1,500 light years away. The striking nebula is visible to the naked eye – and positively breathtaking as seen through the Hubble Space Telescope. Hubble's sharp images, like this one from 2009, have revealed 42 protoplanetary discs (proplyds) where planet formation is now in progress. Theta^1 Orionis C, the nebula's brightest star, heats nearby proplyds, giving them a bright glow. Proplyds forming further away are too dim to see, but their dark dust blocks out parts of the bright nebula in the background, creating silhouettes astronomers can study.

132-1832
Developing far from Theta^1 Orionis C, 132-1832 is one of the darker proplyds in the nebula.

206-446
Astronomers believe this bright proplyd's distinctive ponytail-style plume is a jet of matter streaming out from the disc's centre.

106-417
Stellar wind from the massive Theta 1 Orionis C interacting with gas has formed a shockwave around this ear-shaped proplyd.

180-331
Proplyd 180-331, another bright disc near Theta^1 Orionis C, also sports a flowing jet of matter, giving it a tadpole shape.

181-825
But the best shockwave sculpture has to be 181-825's distinctive galactic jellyfish form.

231-838
Like 106-417, the bright proplyd 231-838 is surrounded by a shockwave, giving it a boomerang shape.

> "The origins of Jovian gas giant planets, like Jupiter and Saturn, are less certain"

Discovering a protoplanet

Dr Simon Casassus of the University of Chile talks us through these fascinating images of a protoplanetary disc in action more than 450 light years away

In January, the University of Chile published images showing a protoplanetary disc in action around HD 142527, a young star over 450 light years away. Can you describe the data shown in the image?

This is a protoplanetary system seen face-on. In red is the thermal emission from rocks or tiny pebbles or sand grains. The size of these particles is about one millimetre. The rest of the colours are gaseous. In green, we see the Formyl ion molecule and in blue we have carbon monoxide. In a lighter blue, there are two filaments crossing the cavity that converge on the centre where the star would be. Those filaments are faint compared to the rest of the nebula, but they are there. This is the first time we've seen such cavity-crossing flows. The other first is the (darker) blue, the diffused carbon monoxide, which is slightly less dense material, more rarified gas.

We think that (gas) giants have formed first through a rocky core… a super-Earth exoplanet, something like ten times the mass of the Earth, which is massive enough to attract and hold the gas in the disc, so it sucks away a cavity, which goes into the body of the planet. So the planet grows at the expense of the disc and clears away a cavity. The size of the cavity we see in this system suggests it's been carved out by several planets. This is what the hydro-simulations tell us. The race is on to detect those protoplanets and thereby confirm the whole theory.

The planet is growing and at the same time clearing away this cavity. The way it manages to keep on growing is by sucking material from the outer regions. This material falls on to the star and crosses the planets as they fall, because they're being perturbed by the gravitational interference from the planets. They catch some of the falling material. But the rest of it just overshoots and reaches the inner disc, which is the other side of the cavity. The rate of inflow of material here is just about right to sustain the continuous growth of the star.

Does this reflect something that happens in most cases of planet formation or is this a special case?

We don't know. Before we can extrapolate to other planetary systems, and before we can conclude that for sure the early Solar System looked like this, we have to find some other examples. This is the first time we have seen these radial flows and this residual gas inside a planetary cavity, and we detected the features at the limit of the capabilities for ALMA in its first year of operations. So we need to study it in more detail and collect similar data around other young stars.

Was there any data in your findings that challenged existing models of planet formation?

That's a hard question because there are so many different models of planet formation. But there are some versions of planet formation which predict very late formation of planets, slower than tens of millions of years, and this one is about two million years.

Is it possible that our own Solar System followed a similar sequence of events?

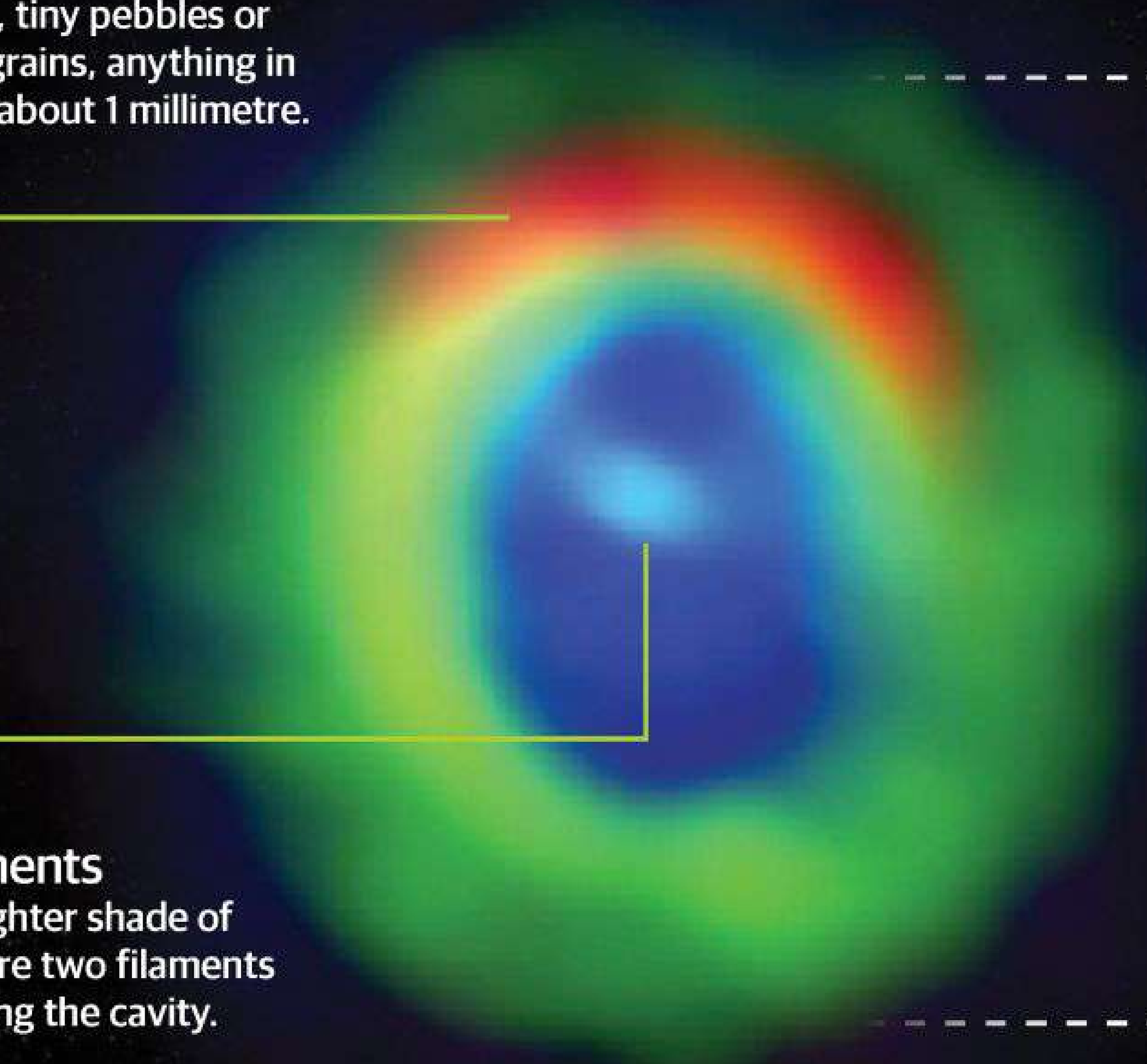
Could be. That's what's so astonishing. If you consider this nebula, it's a protoplanetary disc around the star called HD 142527. In this system the protoplanets are formed really far out from the star. Our hydro-simulations tell us that the protoplanets form around 100AU from the star, whereas Jupiter is at 5AU [from our Sun]. So, is this system comparable to our Solar System? At first, you would say, no, because it's so much bigger. But you also have to think about planet migration. Newborn planets migrate. It is possible for a gaseous giant to migrate from the outer regions at 100AU down to 5AU.

Are there other theoretical phenomena that you're looking to see in future observations?

Yes. There are proto-lunar discs, the circumplanetary discs, which we hope to detect. This would be a way to pinpoint the location of protoplanets.

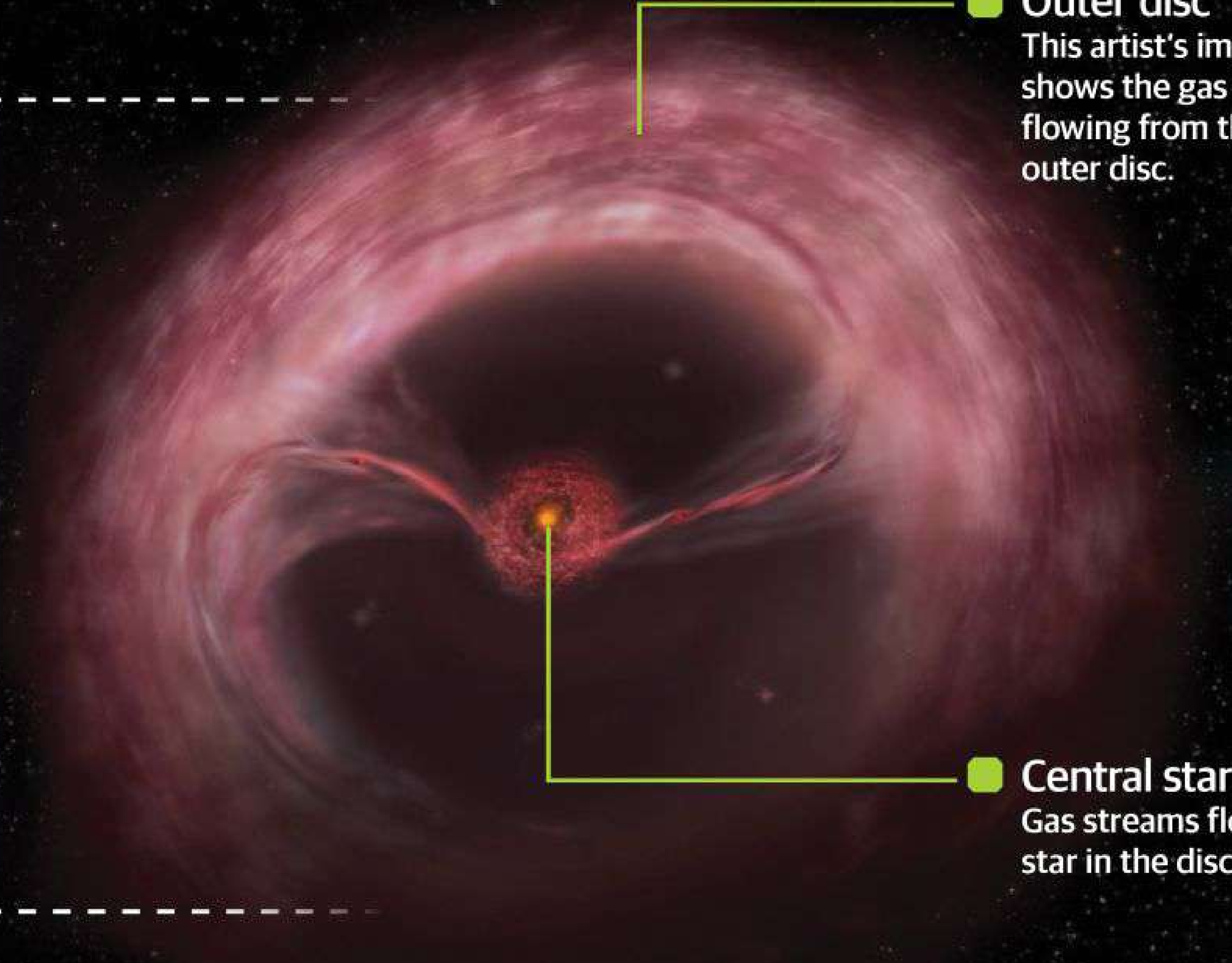
What's next for your team?

We are still analysing this data. And then I'm expecting the rest of the ALMA data and also complementary infrared observations. In the hope of detecting the protoplanets, we applied a variety of techniques.



Thermal emissions
Rocks, tiny pebbles or sand grains, anything in red is about 1 millimetre.

Filaments
The lighter shade of blue are two filaments crossing the cavity.



Outer disc
This artist's impression shows the gas streams flowing from the outer disc.

Central star
Gas streams flow to the star in the disc's centre.

5 AMAZING FACTS ABOUT

Lava worlds

Over half as hot as the Sun's surface

These rocky planets are entirely covered in molten lava and can have a surface temperature up to several thousand degrees Celsius, hot enough to melt most metals.

Earth was once in a similar state

It is thought that between two and three billion years ago Earth's surface was covered in molten lava to a depth of 10 to 15 kilometres (six to nine miles) due to an impact with a Mars-sized object.

Can be torn apart by their stars

Similar to the way the moon Io in our Solar System is stretched and squashed by Jupiter, some lava worlds get their molten surfaces from tidal heating caused by their tight but eccentric orbits.

On some lava worlds it rains rock

The exoplanet COROT-7b orbits so close to its star – 23 times closer than Mercury does our Sun – that its atmosphere consists mostly of vaporised rock, which periodically rains down on the planet.

A year on a lava world can last a few hours

Some lava worlds are planets that orbit very close to their host star. For example, Kepler 78b completes an orbit of its star, Kepler 78, in just 8.5 hours because of its close proximity to the star.

Lava worlds are among the least hospitable places in the universe

THE HUNT FOR EXOPLANETS

Meet the scientists who are hunting for worlds outside our Solar System in an attempt to find Earth-like planets that, like our own, could be hospitable to life

Written by Jonathan O'Callaghan

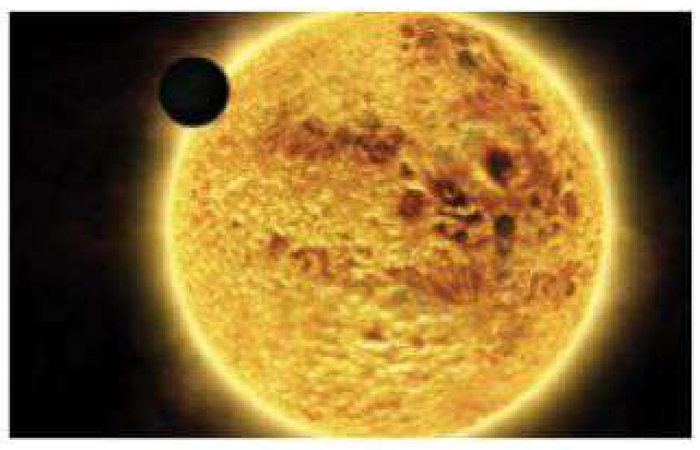
Up until 1992 the thought that there might be other sentient life out there in the universe was one that was generally met with incredulity and disbelief. Those branding aliens as real were looked upon disdainfully, and the mere suggestion that humans were just one of many types of life in the cosmos was not one that was given much credibility.

However, the discovery of an exoplanet (one outside our Solar System) orbiting the pulsar star PST B1257+12 in 1992 changed our entire preconception of the universe. If these planets could exist around such a volatile star, then surely they could also be found around more serene stars and especially those like our own Sun, where we already know the eight planets of our Solar System exist. And of course we also know one planet in our Solar System, Earth, is capable of supporting life. Extrapolating that ratio, there could be billions of Earth-like planets in our Milky Way alone.

The astronomers who found that first planet were Dr Dale Frail and Dr Aleksander Wolszczan. "We didn't begin by looking for planets," said Dr Frail. "We just found this unusual pulsar that was behaving in ways we didn't understand. It turned out to be the most robust planet discovery at the time. I remember very distinctly in 1992 that the planet-hunting community was thrilled about our pulsar planet discovery, because it really told them that they were on the right track, they just need to keep persisting. I think the field was struggling both financially and technically at the time, but the attitude after our discovery was that if planets can form around pulsars then they could form around anything. We gave a real boost to that community."

And so, the hunt was on. Where previously planet hunters had struggled to gain funding, the search for exoplanets shot to the top of agendas throughout the world. Agencies from NASA to Roscosmos to ESA began designing and developing planet-hunting telescopes, while private observatories began to devise techniques that would enable astronomers to search for planets around distant stars.

Methods of finding exoplanets

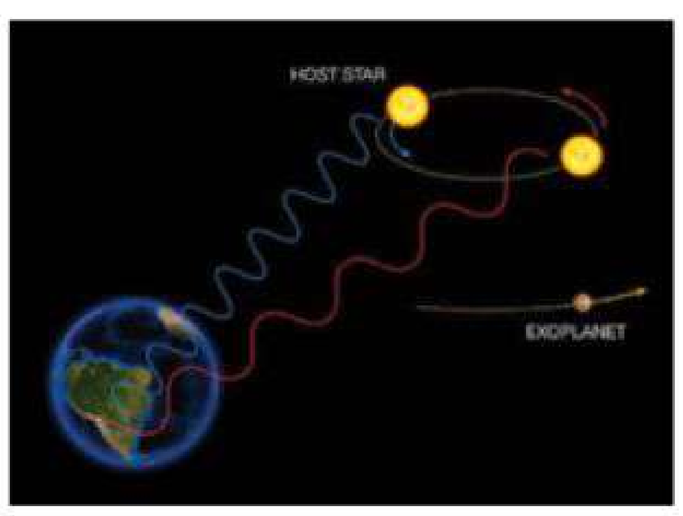


Transit method

As a planet passes in front of a distant star, it will cause a dip in the brightness of the star relative to us. Therefore, by measuring the brightness of many stars at once, we can detect the transits of planets as they pass in front of a star. This method is useful for finding a lot of planets, and it can also determine the mass and size of the planet as well as its orbital period. It is currently the favoured method of planet hunting, used by NASA's Kepler telescope among many others.

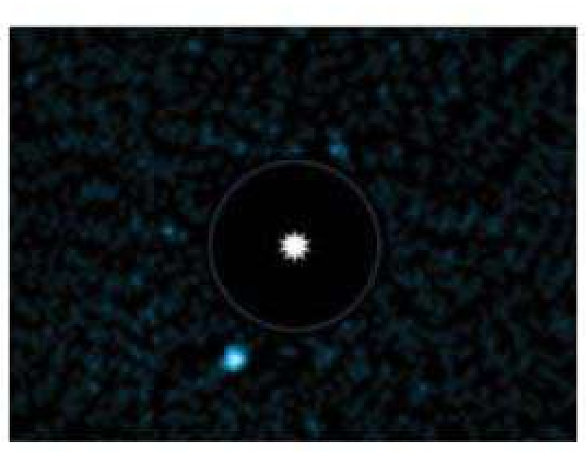
Microlensing

This method of finding planets relies on observing perturbations in a star caused by an exoplanet. To do this the star must be aligned with a background object, such as a galaxy or another star, and as the light from that background object passes around the planet, any exoplanets present will distort the incoming light and indicate their presence.



Radial velocity

By measuring the wobble of a distant star induced by the presence of a planet, just as our own Sun wobbles slightly due to planets such as the Earth, an exoplanet can be confirmed to exist. It's a tricky technique but it was favoured in the early days of planet hunting, although it has now been usurped by the transit method as the preferred method of finding planets.



Direct imaging

One of the most exciting methods of finding exoplanets is direct imaging. As its name suggests, direct imaging relies on telescopes taking actual pictures of planets around other stars. This is done by blocking the light of the star to find planets in orbit. Some direct imaging has already been done, and future telescopes will be expected to produce more and more images of distant worlds.

The initial favoured method that was used to find planets was the radial velocity technique, which observes perturbations in a distant star to indicate the presence of a planet. The current preferred way to find planets, however, is the transit method. To date thousands of planetary candidates that we know of have been found using the transit method, which we'll explain more about later.

But while telescopes around the world trained their sights on potential planet-bearing stars, finding new worlds was proving rather difficult. Up until 2009 barely a hundred planets had been found and confirmed and, owing to the primitive methods available to find them, most of these were giant hot Jupiters with close orbits around their stars – worlds that would be inhospitable to life as we know it.

Finding large planets of this type is much easier because the methods used rely on an observational change in the host star, whether it's a gravitational wobble or a dip in its light as the planet passes in front of it relative to us. A large planet orbiting at high speed will produce frequent and noticeable effects on the star, whereas a smaller planet in a slower orbit further out is much harder to detect. To find smaller planets, and therefore ones that are more similar to Earth, astronomers needed a way to watch thousands of stars simultaneously rather than just focusing on a few at a time.

Fortunately, NASA had recognised the need for a wide-field observation telescope and had begun working on one at the beginning of the 21st Century. The telescope would be groundbreaking and do something never attempted before. It would be put into an orbit around the Sun, away from any interference, and it would train its sights on a specific area of the Milky Way galaxy. Known as the Kepler

The Kepler telescope before it launched in 2009

The Kepler team studies some of the many transiting planets they've found

The team that started it all

Kepler space telescope

To date, a huge majority of exoplanets we know of have been discovered by the Kepler space telescope team. Launched on 7 March 2009, Kepler sits in an Earth-trailing orbit around the Sun. Before its launch it was considered possible that planets in the universe were rare. Now, however, its thought that almost every star plays host to at least one planet.

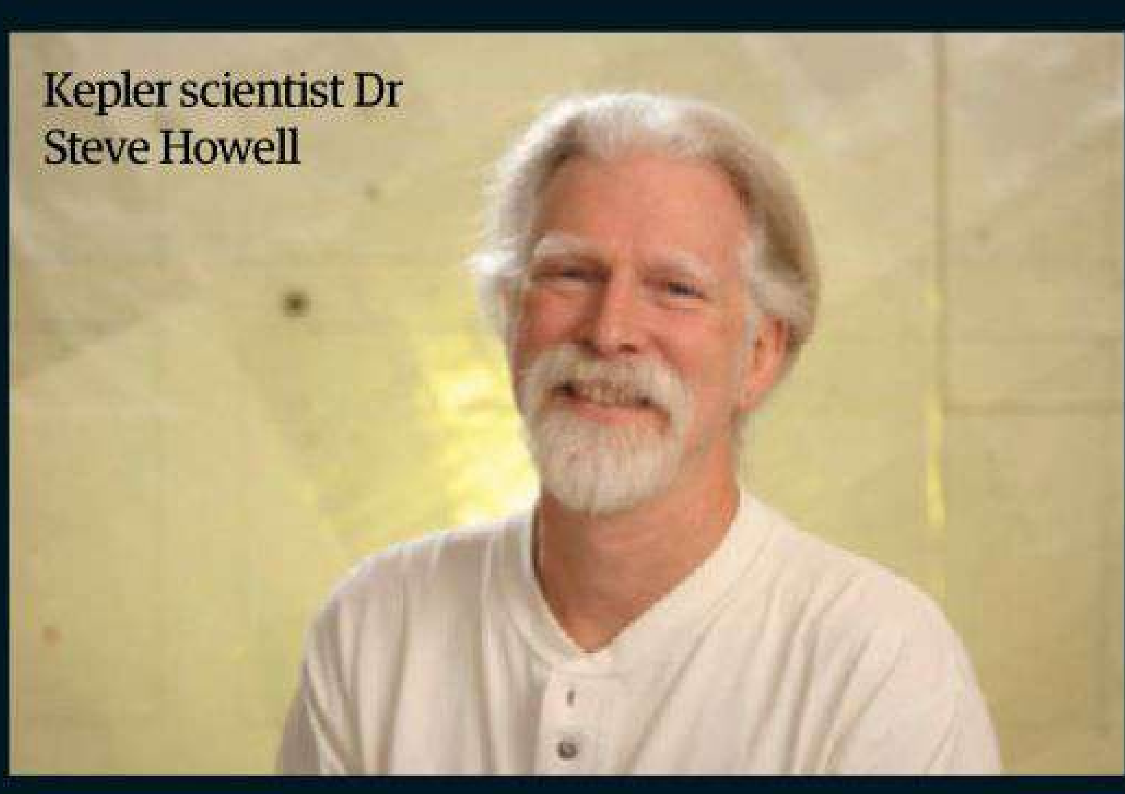
The telescope uses photometry to simultaneously observe thousands of stars. It watches for dips in the brightness of these stars as a planet passes in front, known as a transit, and measuring three of these transits confirms the planet's existence as well as its size owing to the amount the star dims. The orbital period can also be calculated from multiple planets, and ultimately its distance from its host star can be determined. Scientists have been poring over Kepler's data looking in earnest for the holy grail of planet hunting, a world similar in size to our own residing in the habitable zone of its star.

Of the hundreds of planets Kepler has found, though, it was the very first that elicited the most excitement. "The most exciting planet discovery was probably the very first one, when we actually looked at a light curve that came down very early on in the mission almost in real time and you could see the transit by eye," said Kepler project scientist Dr Steve Howell. "It was a planet that had been discovered before Kepler had launched so we knew it was there. It was a really big planet, and, boy, if we couldn't have found that we were in real trouble."

Aside from the early excitement that confirmed Kepler was in full working order, there have been a number of recent discoveries that have been just as interesting. "In the last few months we've found the planets Kepler-69 and Kepler-62 around stars kind of like the Sun," said Dr Howell. "They are planets that aren't much bigger than the Earth and these planets are in their star's habitable zone. They're probably rocky, or at least very water-rich planets. They are very exciting, they are really getting us towards the true Earth-analogue kind of planet."

At the time of writing a fault with one of Kepler's reaction wheels has left the telescope unable to do the precise positional movements needed to perform photometry and find new planets. However, the team are confident that even if the telescope can't continue hunting for planets, there is still plenty of data to be analysed and, even then, it leaves a lasting legacy that has led to the development of other planet-hunting telescopes.

"Kepler's been critically important," said Dr Howell. "I think that if Kepler had not been launched, other planet-hunting telescopes would have never even been thought about, and certainly wouldn't have been selected [for development]. The chances of these missions going ahead have increased because planets are such a hot topic these days."



Kepler scientist Dr Steve Howell

"Kepler-69 and Kepler-62 are in their star's habitable zone" **Dr Steve Howell**

Kepler in numbers

The telescope's facts and figures

132

Kepler has found 132 confirmed planets so far

17%

A planet 0.8-1.25 times the size of Earth is believed to reside around 17% of stars

50%

About half of the planets Kepler has found have been Neptune-sized

100k

Number of stars that Kepler has observed in hunt for planets

2,740

A further 2,740 planetary candidates are awaiting confirmation as fully fledged worlds

SuperWASP team member
Dr Don Pollacco

Looking for strange new worlds

SuperWASP (Wide Angle Search for Planets)

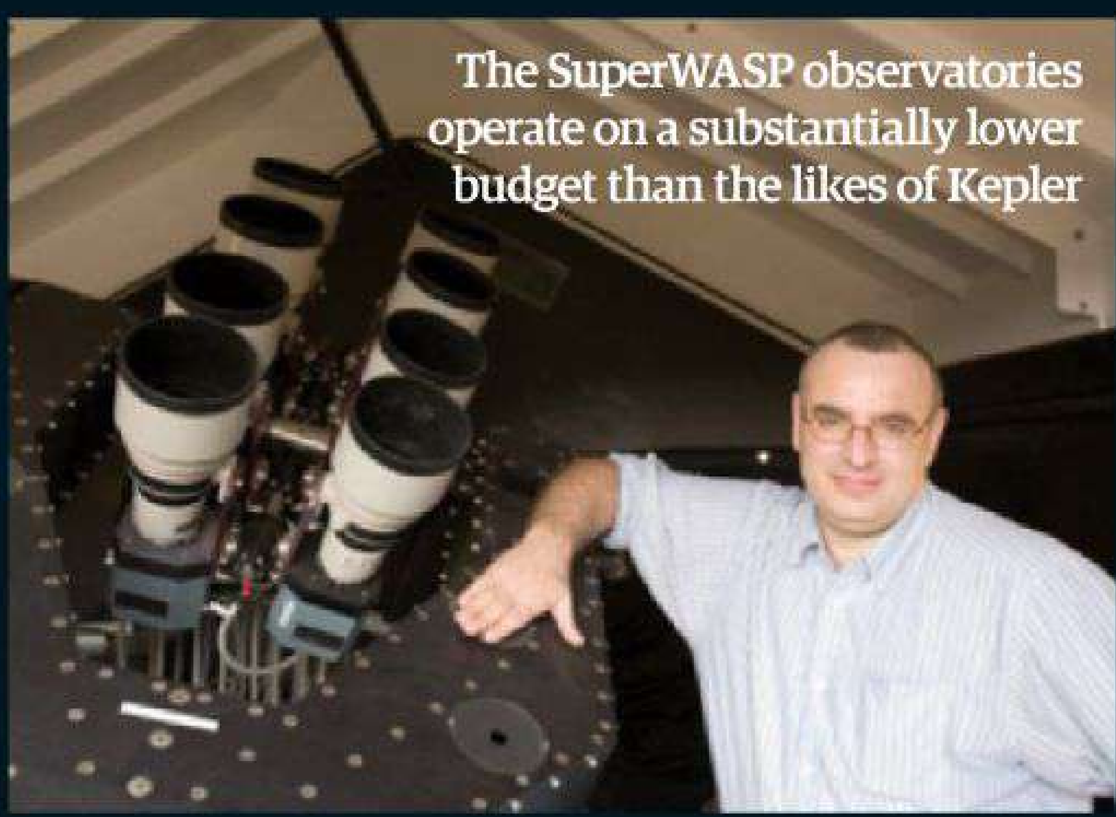
While telescopes like Kepler cost hundreds of millions of dollars, planet hunting doesn't require a fortune to succeed. One such project is SuperWASP (Wide Angle Search for Planets), which at a cost of just half a million dollars has found over 100 planets outside our Solar System. SuperWASP has two robotic observatories, one on the island of La Palma in the Canary Islands and the other in South Africa. Each has eight lenses backed by high-quality CCDs to monitor stars and search for new worlds.

"We can't compete with [the programmes] that find small rocky planets, but we can find unusual things still," said SuperWASP team member Dr Don Pollacco. The two observatories have mostly been responsible for finding hot Jupiter-like planets, and SuperWASP can help to determine how abundant certain types of planets are in the universe.

One thing in particular that SuperWASP has helped to understand is how some of these planets got into very tight orbits around their star. "One thing SuperWASP has done over the years is that it has basically discovered that most of these planets that are close in have probably got there by interactions with other planets," explained Dr Pollacco. "If you look at something like Pluto, what you find is that Pluto is going in the opposite direction [to the rotation of the Sun]. What that tells you is that Pluto was never born where it is now, it's been somehow perturbed into that orbit."

Of SuperWASP's most notable discoveries, Dr Pollacco cites the exoplanet WASP-12b as one of his favourites. "WASP-12b is a really highly inflated planet, so it's got a mass of Jupiter but it's nearly twice Jupiter's size," he explained. "What that really tells you is there's some extra energy source going on in this planet that's inflating it, and there are a number of other planets like that, but we don't understand them."

Next up for Pollacco and the SuperWASP team will be to begin a new experiment called the Next Generation Transit Survey. "We're very close now to being able to detect planets with periods of maybe 100 or more days," explained Dr Pollacco. "They will potentially be two or three times the size of Earth and maybe ten Earth masses, so they're potentially rocky planets. And we're doing this all from the [surface of the Earth], you don't need to spend $600m [on a space telescope] to do it."



The SuperWASP observatories operate on a substantially lower budget than the likes of Kepler

One SuperWASP observatory is in the Canary Islands and the other is in South Africa

"You don't need to spend $600m to hunt for planets" **Dr Don Pollacco**

The WFIRST programme team, who recently received funding from NASA with a view to launching the WFIRST planet-hunting telescope in 2023

space telescope, NASA's newest creation would prove to be the most important and useful planet-hunting telescope to date.

The Kepler telescope launched in 2009 to its predetermined position 150 million kilometres (93 million miles) from Earth in orbit around the Sun. It uses the aforementioned transit method to find new planets. To understand how it works, imagine you were staring at 20 light bulbs in a grid, and you knew some of these light bulbs had moths flying around them but you weren't sure which. You observe the bulbs for a period of time and each time one of the bulbs dims you can presume that something has passed in front of it. By observing the dip in the light three times and measuring the time taken for the dips to occur, you can confirm that there is something flying around the bulb and you can work out the speed the object is moving at. With just this data alone, you can even measure the dip in brightness and, coupled with the knowledge of its orbital period and the size of the bulb, you can deduce the size of the object. From just these three calculations you know the speed of the moth, its size and its distance from the bulb.

Kepler does this for 100,000 stars. So it observes all of them simultaneously, watching out for dips in their brightness, and then waits to confirm the regularity of the dips. By doing so it can deduce if there is a planet present around the star and then calculate its speed, size and distance from the star. At the time of writing, the Kepler space telescope is currently out of operation after losing functionality in one of the reaction wheels that allows it to accurately focus on these distant stars, but regardless, since it was launched it has provided scientists with a multitude of data to find new planets, much of which will take another two years to analyse. The field of planet hunting has been kick-started by Kepler with numerous projects now in operation around the world to find planets.

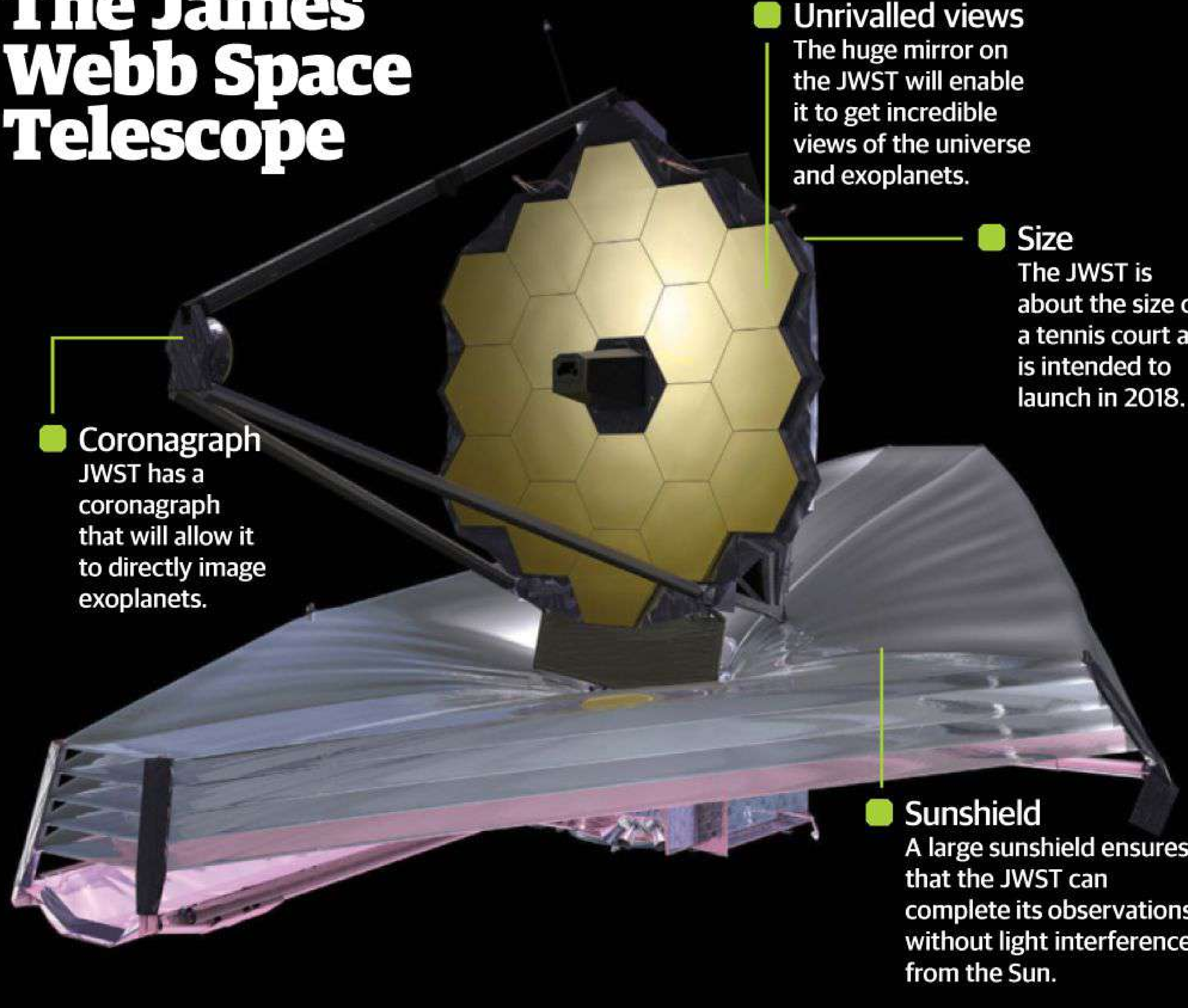
The detection of exoplanets has proved beyond reasonable doubt that almost every star in the universe plays host to a planet of some sort. However, as mentioned earlier the majority of planets we've found so far have been large Jupiter-sized worlds, many orbiting their stars in tight orbits and therefore having a scorchingly hot temperature. The holy grail of planet hunting is to find a world exactly like Earth, with the same size and mass in an orbit in its star's habitable zone, where conditions are just right - not too hot and not too cold - and therefore water will be able to form. To date, no such world has been found.

> "We'll find thousands of exoplanets using the microlensing technique, and even some in the habitable zone" **Dr Neil Gehrels**

However, in January 2013 astronomers at the Harvard-Smithsonian Center for Astrophysics reported that there were likely to be at least 17 billion Earth-sized worlds in our Milky Way galaxy alone. When you consider that there are hundreds of billions of galaxies in the universe, it is therefore highly unlikely that only one of these, our own Earth, is able to play host to life.

One of the difficulties in finding Earth-like worlds is the limiting factors of the methods we currently use to find planets. The transit method, for example, relies on multiple observations of the orbit of a planet around a star. Consider looking at our Sun from outside the Solar System; to definitively detect the Earth you would have to observe three transits of the Earth on the Sun, which would take three years. Therefore, only by observing stars for a long period of time can planets in habitable orbits be found. The Kepler telescope has so far completed over four years

The James Webb Space Telescope

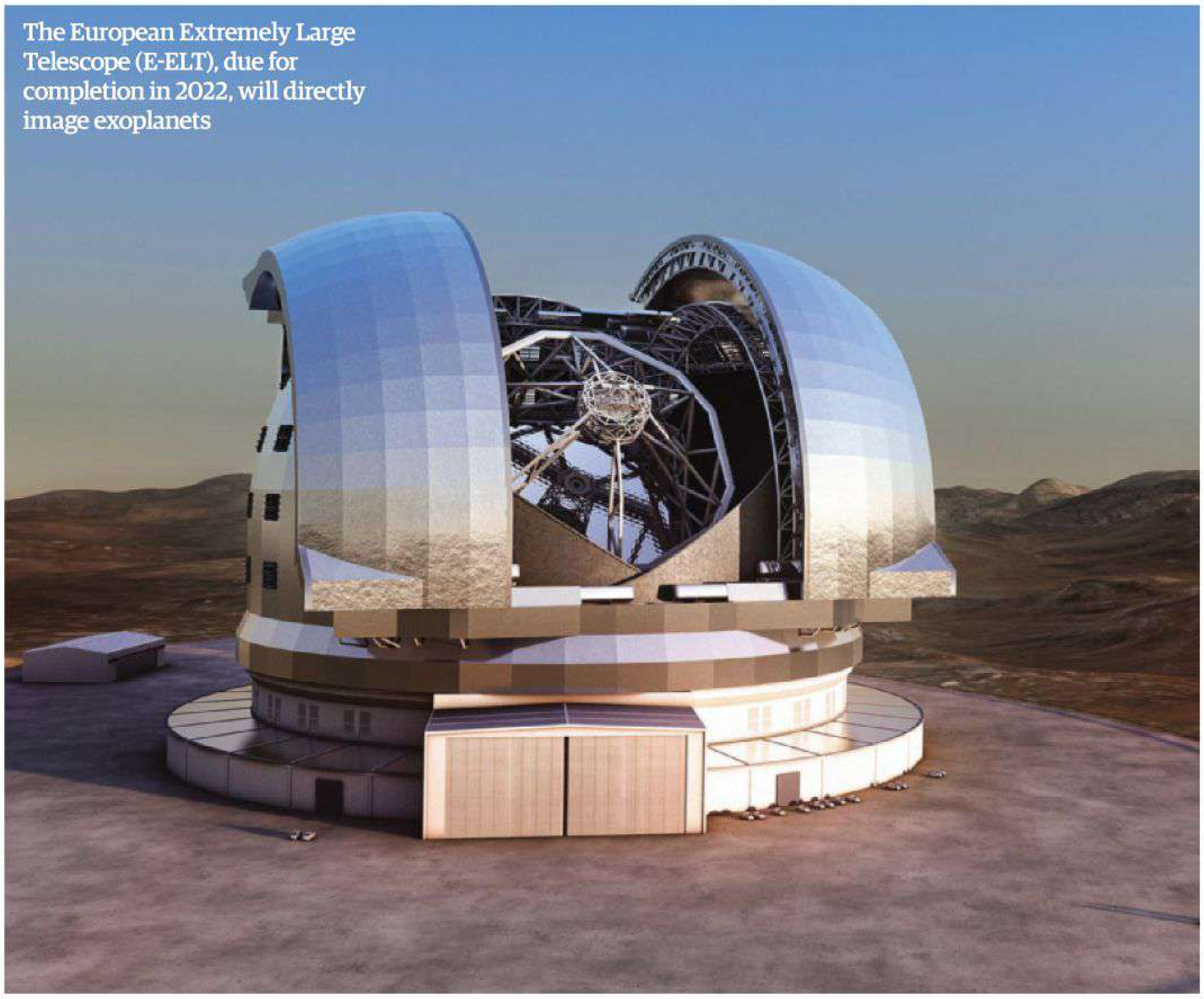


Unrivalled views
The huge mirror on the JWST will enable it to get incredible views of the universe and exoplanets.

Size
The JWST is about the size of a tennis court and is intended to launch in 2018.

Coronagraph
JWST has a coronagraph that will allow it to directly image exoplanets.

Sunshield
A large sunshield ensures that the JWST can complete its observations without light interference from the Sun.


The European Extremely Large Telescope (E-ELT), due for completion in 2022, will directly image exoplanets

of observations, so it is hoped that within its data may be hiding some of these Earth-like worlds. It's also thought that some habitable planets might reside in closer orbits around red dwarfs, which would mean their orbits are slightly faster and therefore detection might be easier

Perhaps, though, to increase our chances of finding a new Earth we need to change our methods of finding planets. One of the most promising techniques that has already been tested, and will be used more in future, is directly imaging exoplanets. Some modern observatories such as the European Southern Observatory's (ESO) Very Large Telescope (VLT) have already been able to take images of planets, and future telescopes like NASA's James Webb Space Telescope and the European Extremely Large Telescope will be able to continue this work.

To directly image a planet, the light of its host star must be blocked out using something called a coronagraph. This allows observations of the area around a star to be made, and any planets in orbit will be somewhat visible. Understandably, though, the method is incredibly difficult. "Smaller telescopes don't have a good enough angular resolution, so they don't have good enough imaging precision to really use a coronagraph," said Dr Neil Gehrels, one of the scientists on the WFIRST programme. WFIRST is a telescope that has recently received funding from NASA with a view to a launch in 2023. It will search for exoplanets using both the microlensing technique and possibly by directly imaging them.

"We'll find thousands of exoplanets using the microlensing technique, and even some that are in the habitable zone, similar to Earth-like planets," explained Dr Gehrels. "But then with the coronagraph, the really exciting thing we can do is to make a direct image of an exoplanet. We might

"With the coronagraph, the really exciting thing we can do is to make a direct image of an exoplanet" **Dr Neil Gehrels**

Types of exoplanet

Rocky
Many of the smaller worlds found so far have been found in tight orbits around their star, meaning they are probably both hot and rocky with more of a resemblance to Venus than to Earth.

Earth-like
The holy grail of planet hunting is to find a world the size of Earth orbiting its star within the habitable zone. So far we haven't found one, but most scientists expect such a discovery to be made in the next few years.

Super-Earth
Planets found in habitable zones so far have tended to be much larger in both size and mass than the Earth. This has led scientists to postulate that these giant worlds could bear water and possibly even life.

Hot Jupiter
The majority of planets found to date are hot Jupiters, giant gas planets orbiting very close to their host star. In recent years larger planets have also been found orbiting further away from their star.

Imaging exoplanets

The James Webb Space Telescope

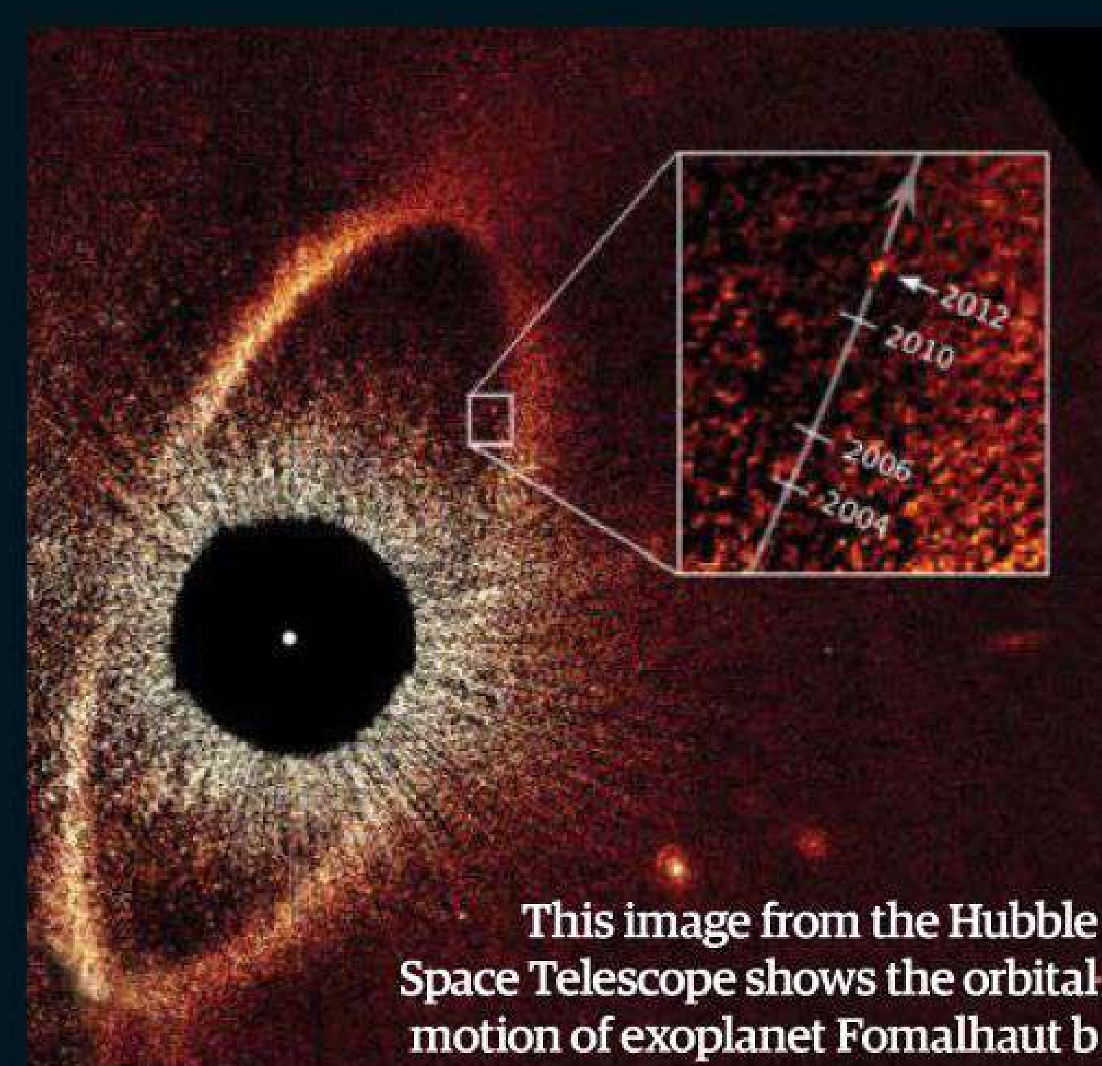
The most exciting area of planet hunting currently being developed is undoubtedly that of direct imaging. To directly image exoplanets, something known as a coronagraph is used, an instrument present on several telescopes including NASA's Hubble Space Telescope. This blocks the light of the host star, allowing the scope to see around the star and possibly detect a planet. On the right of this page you can see an incredible composite image of a dust disc around the Fomalhaut star taken by Hubble, and within this disc a planet called Fomalhaut b was discovered on a 2,000-year orbit around the star.

"We knew there was a ring [around Fomalhaut] but we didn't really have very high hopes of being able to see it, so we were kind of surprised when we actually found this very nice ring," said Dr Mark Clampin, one of the discoverers of Fomalhaut b and a project scientist working on the JWST. "When we were going through our data we found there was a point source there [indicating a planet] that we were not expecting to find. So we started to study this planet around Fomalhaut and not the ring."

One of the difficulties, however, is that planets tend to be very dark. Their host star must be sufficiently bright to enable the planet to be seen as it reflects more light, or the planet needs to have characteristics that make it more visible. "The reason we could image [Fomalhaut b] is because it's a lot brighter than it should be," continued Dr Clampin. "It looks like the planet has a big ring of dust around it like Saturn, and that dust is boosting the light of the planet so it appears brighter."

The launch of JWST, though, will provide the biggest boost for planet imaging. "JWST consumes my every waking hour at the moment," said Dr Clampin. "I'm really looking forward to JWST because I think, while it won't be able to directly image rocky planets, it will do a really fantastic job of studying planets around younger stars. And using different techniques like transit spectroscopy [studying a planet as it passes in front of its host star] we will be able to make observations of planetary atmospheres around super-Earths."

> "We will be able to observe planetary atmospheres around super-Earth" **Dr Mark Clampin**



This image from the Hubble Space Telescope shows the orbital motion of exoplanet Fomalhaut b


Dr Mark Clampin is project scientist on the James Webb Space Telescope and currently works on imaging exoplanets


Here the JWST team stands in front of a full-scale mock-up of the giant space telescope

Amazing Earth-like worlds

Gliese 667C c

Distance from Earth: 22 ly
Orbital period: 28 days
Size: 1.9 Earth radii

This planet is one of the best candidates for a world harbouring liquid water. While slightly warmer than Earth, its residence in its star's habitable zone coupled with a terrestrial mass increase its chances of being home to life.

Tau Ceti e

Distance from Earth: 12 ly
Orbital period: 168 days
Size: 1.8 Earth radii

Still to be confirmed, this nearby planet holds evidence that it may be hospitable to life. It's towards the hotter edge of its star's habitable zone and could have a thick atmosphere.

Gliese 163 c

Distance from Earth: 49 ly
Orbital period: 26 days
Size: 1.8-2.4 Earth radii

This potentially habitable planet orbits a red dwarf star but, with a mass 72 times that of Earth and near to its star, it may be too hot for life. Planets around red dwarfs are still not fully understood though, so it may have some unknown characteristics.

Earth not to scale

HD 40307 g

Distance from Earth: 42 ly
Orbital period: 198 days
Size: Unknown

The orbit and position of this planet makes it a suitable candidate for one that could support life. At the moment though scientists aren't sure if it's a super-Earth or a warm Neptune without a solid surface.

Gliese 581 d

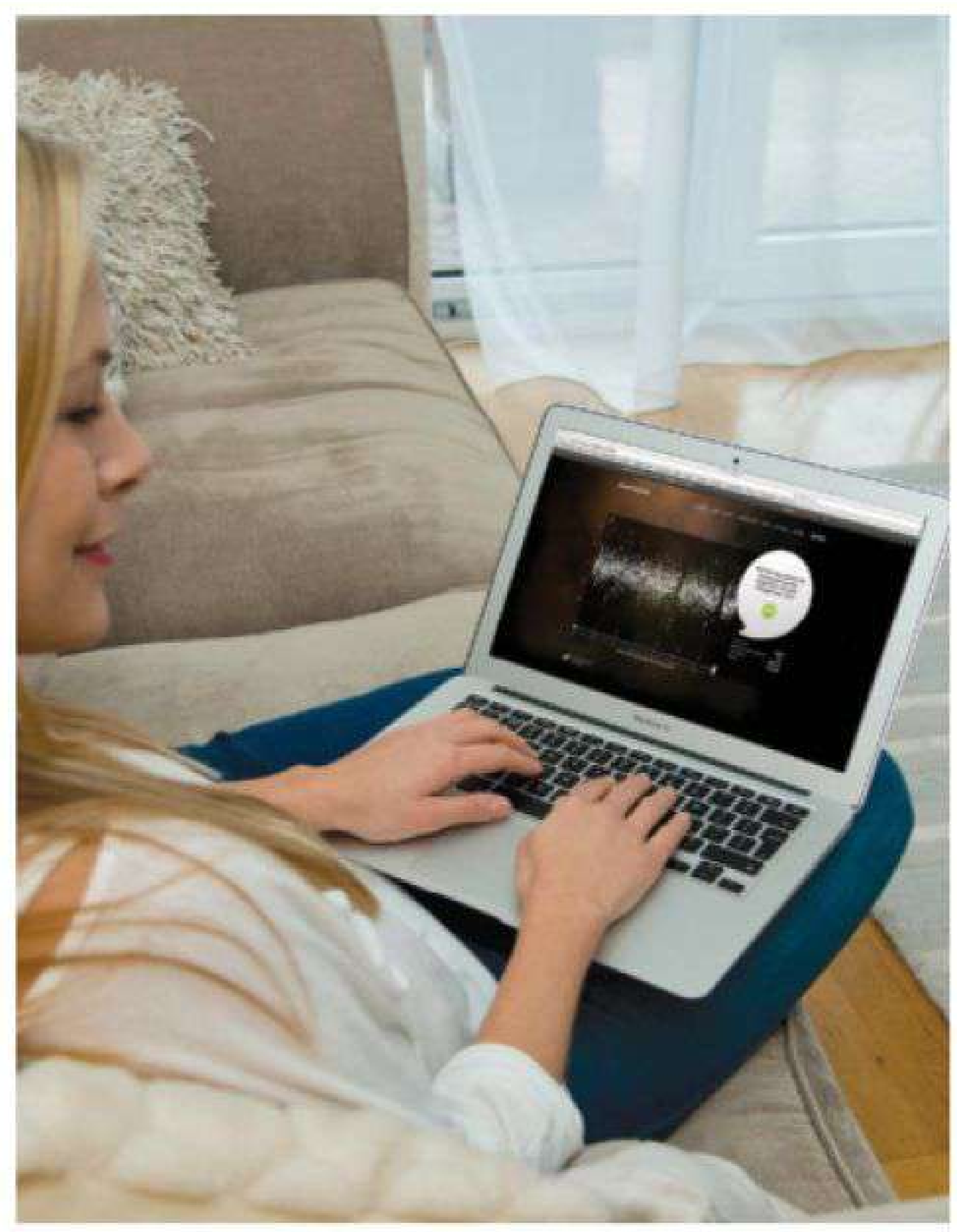
Distance from Earth: 20 ly
Orbital period: 67 days
Size: Unknown

This planet in the Gliese 581 planetary system was the first example of a terrestrial-mass planet orbiting in the habitable zone of its star. Despite being considerably larger than Earth, its discovery hinted that smaller habitable planets could be found.

be able to get close in to Earth-mass worlds. The telescope has spectroscopy on board, so we could look at the constituents in the atmosphere."

As Dr Gehrels mentions, studying the atmospheres of exoplanets is another area of planet hunting that has garnered a lot of interest recently. By analysing the light of a star as it passes through a planet and studying the changes in its spectroscopy, scientists are able to determine what sort of atmosphere the planet might have. Some telescopes like the aforementioned James Webb Space Telescope may even be able to make direct analysis of alien atmospheres, finding out if they bear any similarity to ours on Earth and, ultimately, possibly indicating that the planet is habitable.

Every month we seem to hear of an exciting new exoplanet discovery, and as more and more telescopes come online we will continue to find amazing new worlds that are not only similar to Earth but are in fact so dissimilar that they question our current theories of planet structure and formation. Thanks to telescopes like Kepler scientists have a great starting point to search for planets. They already know of thousands of stars with planets in our Milky Way, and as our methods of detection and analysis improve we will move closer and closer to finding a world like our own.



How you can become a planet hunter

Planet hunting isn't just for professional scientists and astronomers. If you want to start searching there are a number of projects on the internet that you can get involved with to help sift through data to find planets. One such project is found online at planethunters.org, where you can view graphs of the light emitted from distant stars to find planets using the transition method. Who knows, perhaps you could help find the first true Earth-like world?

Rogue planets

Planet expert Thijs Kouwenhoven tells us why these nomad worlds are so important

"If the Earth were ejected temperatures would drop beyond the freezing point of the atmosphere "

Thijs Kouwenhoven, planet expert

Just eight planets make up our Solar System, ranging from the rocky terrestrial inner worlds to the huge outer gas giant planets, and based on our understanding of exoplanets so far it appears that there are many other planetary systems both like and unlike our own around other stars. But could there be planet-sized objects drifting through the universe unattached to a host star or planetary system?

"Rogue planets, also known as free-floating planets [FFPs], are planets that are freely floating through space. They are not orbiting a star or any other massive object, such as a white dwarf or black hole," says Thijs Kouwenhoven, the co-author of a paper entitled 'On the origin of planets at very wide orbits from the re-capture of free floating planets' with colleague Hagai Perets. The two have been pivotal in the study of rogue planets, and believe that the universe is teeming with these nomad worlds that may have once been part of a planetary system like our own.

"Theory suggests that all rogue planets are formed through the ejection of planets from planetary systems," says Kouwenhoven. "If we look at our Solar System, we see that comets and asteroids can be ejected with high velocities when they come too close to Jupiter or Saturn. In the same way, a planet can be ejected from a planetary system after a strong gravitational interaction with another planet. In fact, computer simulations suggest that Mercury is most likely to be the first planet to be ejected from our Solar System in the distant future [in billions of years]."

It's not only the interaction between planets that can deprive a world of its host system, however. Two stars passing close to each other in a crowded part of a galaxy could result in planets being flung from their system. One example of such a region is something known as a globular cluster, a compact collection of stars "where the density of stars is so high that most of the planets are likely to have left their parental star. Star clusters are therefore good places to look for free-floating planets."

While we can simulate their existence, the detection of rogue planets is rather more difficult, not least because our most successful current method of finding exoplanets, namely by observing their transit across their host star, is nigh-on impossible without such a star to transit. Therefore, scientists have been using the microlensing technique (see 'How do we find them?' boxout) to find rogue planets in densely packed regions such as globular clusters.

So, if we can't see rogue planets, how do we know they're there? "Traditionally, the existence of rogue planets came from theory, and later from computer simulations," says Kouwenhoven. "Everyone playing with a simple planetary system simulator on an iPhone, or with the most sophisticated astrophysical software, will notice that many planetary systems are unstable, which often results in the ejection of one or more planets into deep space. Observationally it is very difficult to find free-floating planets. They do not emit light and are almost impossible to see with telescopes. In addition, their mass is much smaller than that of stars. Unlike for the detection of black holes, the gravitational pull of planets on their surroundings cannot be used to infer their existence."

If the theory and simulations hold true, then from our knowledge of planetary systems, and our simulations of the gravitational interaction of planets, the expected number of such nomad worlds according to Kouwenhoven should be huge. "Based on observations, one can infer that there are roughly twice as many free-floating planets as there are stars in the neighbourhood of the Sun," he says. "In crowded environments, such as in the centre of the Milky Way and in globular clusters there may be many more due to the destruction of planetary systems by close stellar encounters. A rough estimate gives 100 to 150 billion rogue planets in our Milky Way galaxy, and there are hundreds of billions of galaxies in the observable universe. That's a lot of planets."

But what of the conditions on such worlds? As they are drifting freely through space, it would be expected that almost all of them would be uninhabitable. With no star to heat their surface, every rogue planet is expected to be freezing cold and therefore it might seem impossible that the surface of any such world is habitable. Hope is not lost, however, says Kouwenhoven: "We know that our planet Earth is very warm on the inside. Sometimes we see molten lava coming out of volcanoes, so the heat source is clearly not the result of the Sun heating up the Earth [but rather a molten core].

"Some rogue planets may also have an internal heat source, just like the Earth. Although the surface of the planet might be frozen, underground oceans could exist due to the presence of the internal heat source. In fact, even in our own Solar System, several cold moons have subsurface water oceans. The most famous example is Jupiter's moon Europa, which has an icy cold surface, but a warm water ocean below. Rogue planets could be habitable to small creatures that like to live in subsurface oceans in total darkness. But it is not a very nice place for humans to go. If the Earth were ejected, the oceans would probably freeze quickly, and temperatures would drop rapidly beyond the freezing point of the oxygen and nitrogen in the atmosphere."

So, do these giant floating rocks pose any threat to Earth? Could they drift into the Solar System and impact our planet? "Yes, this is possible. However, the chances are extremely small, and it is unlikely that this has ever happened or will ever happen. On the other hand, it can happen that the Sun or another star captures a rogue planet into a wide orbit, far beyond the orbit of Pluto. This formerly rogue planet would then have found a parent star again, perhaps after billions of years of loneliness in deep space."

There could be up to 150 billion rogue planets in the Milky Way

How do we find them?

Kouwenhoven explains how we hunt for these lonely worlds: "Einstein's theory of relativity comes to help when finding free-floating planets. The gravity of each object in the universe deflects light. Under certain circumstances, this light deflection can act as a lens, and the light of a background star can be briefly enhanced. When a free-floating planet passes right in front of a background star, the background star suddenly becomes brighter for a brief time, and then faint again. The brightness changes due to microlensing have characteristics that allow the observer to derive the mass of the lensing object. In this way, several objects of planetary mass have been discovered, freely floating through space."

All About... OUR TWIN SOLAR SYSTEM

Part of a triple-star system not far from our own, Gliese 667 C holds the record for having three potentially habitable planets in its orbit

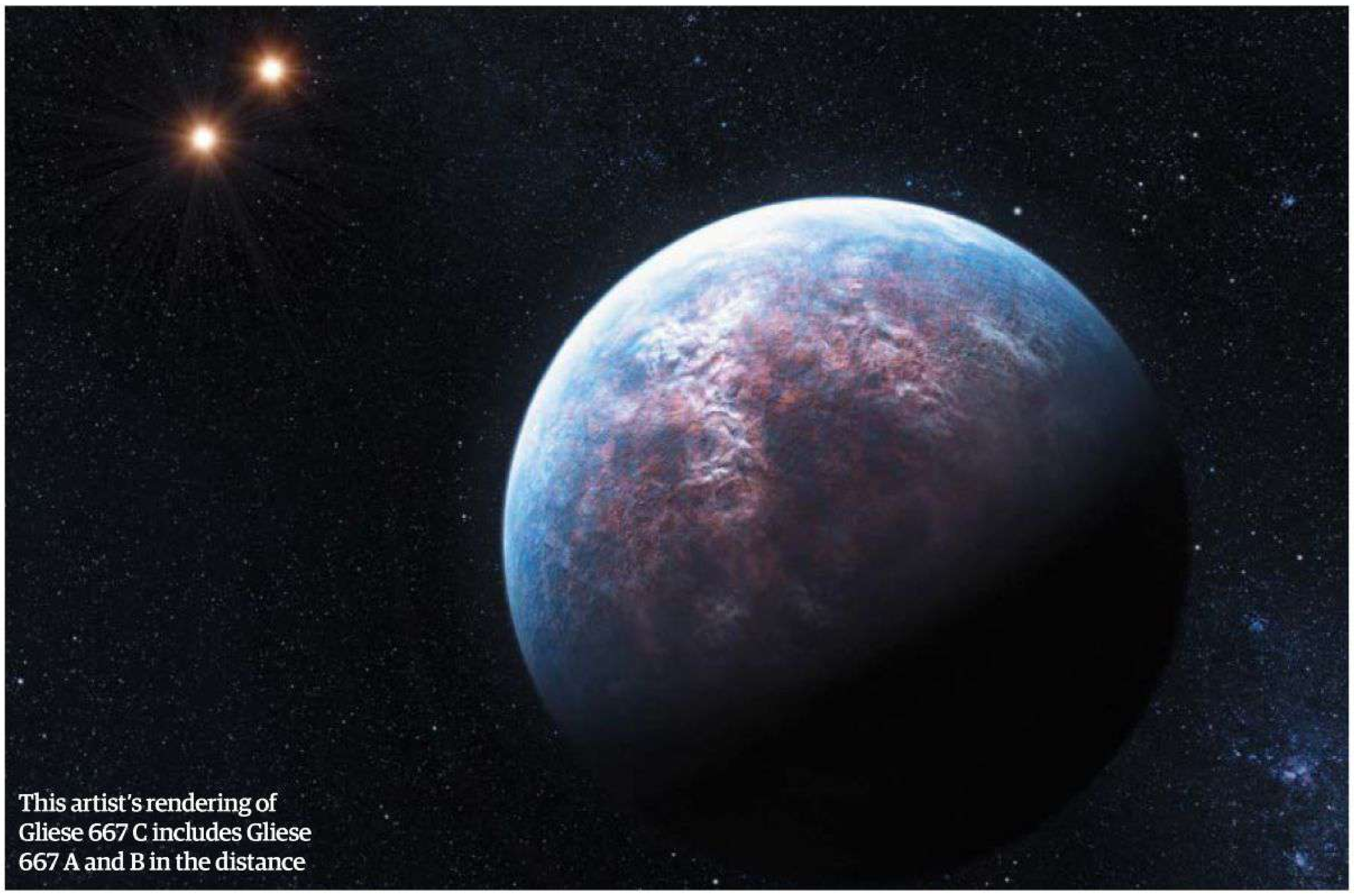
Written by Shanna Freeman

Gliese 667 is located about 22 light years from Earth, and appears to be a single star of about magnitude 5.89 if viewed with the naked eye. Any star above a 6 is considered to be too faint to view without a telescope, so this is a pretty faint star. In reality, Gliese 667 is a triple-star system - a system in which three stars are gravitationally bound to each other - located in the Scorpius constellation. Each of the three stars in the system are much smaller than the Sun.

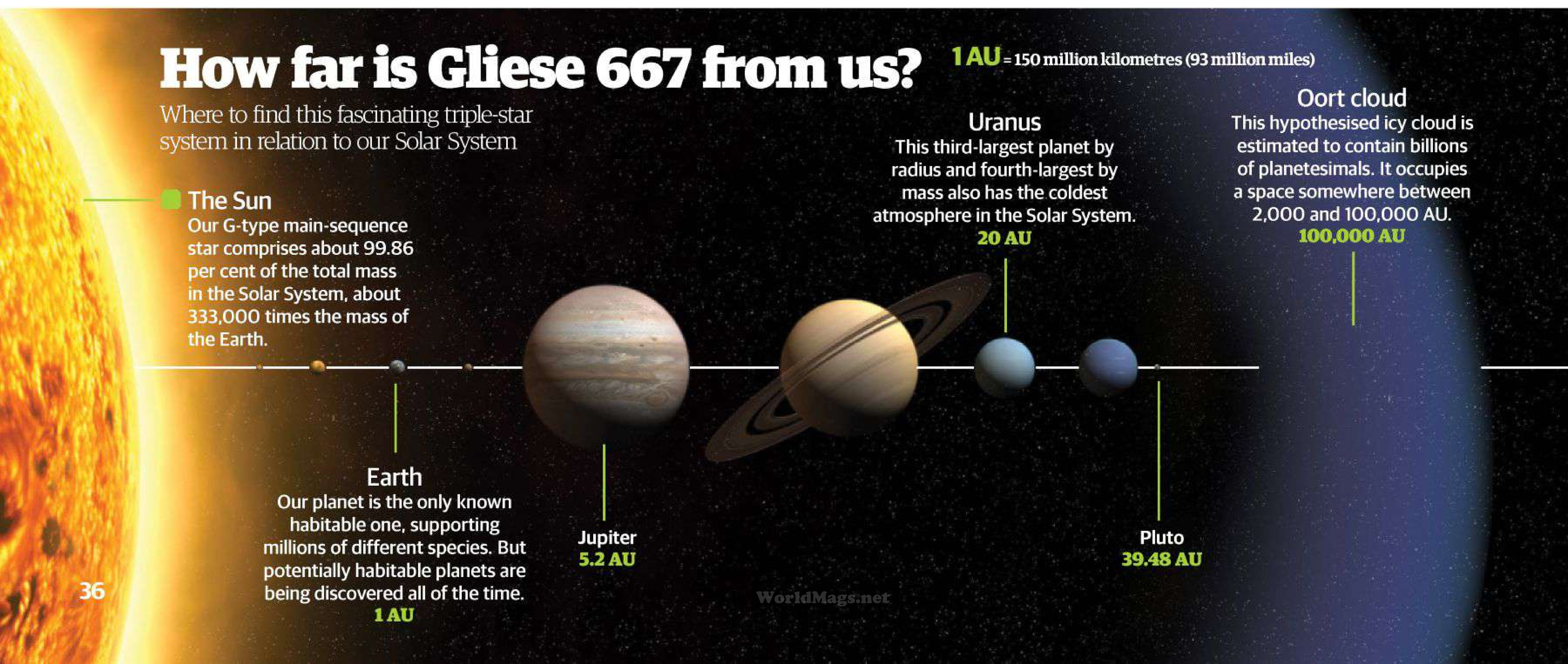
The three stars are named Gliese 667 A, B and C. Gliese 667 A and B are the brightest two stars in the system. Gliese 667 A is a K-type main-sequence star, also called an orange dwarf or K dwarf. The K designation means that it is a relatively cool star, between 3,627 to 4,927 degrees Celsius (6,561 to 8,900 degrees Fahrenheit) on the surface. These stars have masses between 60 and 90 per cent that of the Sun's mass, and stay on the main sequence for longer than the Sun does - 15 to 30 billion years, as opposed to the Sun's ten billion years. Orange dwarfs are up to four times more common than Sun-like stars, and tend to have mostly neutral metals like silicon, iron and manganese in addition to helium and hydrogen. Gliese 667 A radiates about 12 per cent of the Sun's luminosity, but has about 75 per cent of its mass. Gliese 667 B is the secondary star in the system and also an orange dwarf, but it's slightly smaller than A and is a little further along in the main-star sequence. It has a mass about 69 per cent that of the Sun and radiates about five per cent of the Sun's luminosity. Gliese 667 B is also brighter than A. These two stars orbit each other, with an eccentricity of about 0.6. This means that the distance between them varies from 5 AU (astronomical units, or Earth to Sun distances) to 20 AU. It takes about 42 years to complete one orbit.

Because of the long period of time they spend on the main sequence, orange dwarfs present a good opportunity for astronomers to search for extraterrestrial planets. Therefore, it's interesting that the third star in the system - Gliese 667 C - is the one in the system known to have planets in orbit around it. It's an M-class star, specifically a red dwarf. While on the main sequence, these stars are smaller and cooler than orange dwarfs. Their masses can be up to 50 per cent of the Sun and, temperature-wise, red dwarfs are less than 3,727 degrees Celsius (6,741 degrees Fahrenheit) on the surface. Red dwarfs are the most common type of star in the galaxy. Gliese 667 C is believed to have about 30 per cent of the Sun's mass and 42 per cent of the Sun's radius, and is relatively inactive. That makes it ideal for investigating orbiting planets. While Gliese 667 A and B are so close together that they're often grouped on maps as Gliese 667 AB, Gliese 667 C orbits the other two stars at a much further distance. There's a minimum of 230 AU between Gliese 667 AB and Gliese 667 C. We believe that it has at least five, and as many as seven, planets orbiting it. Three of the planets have been dubbed super-Earths and may be habitable.

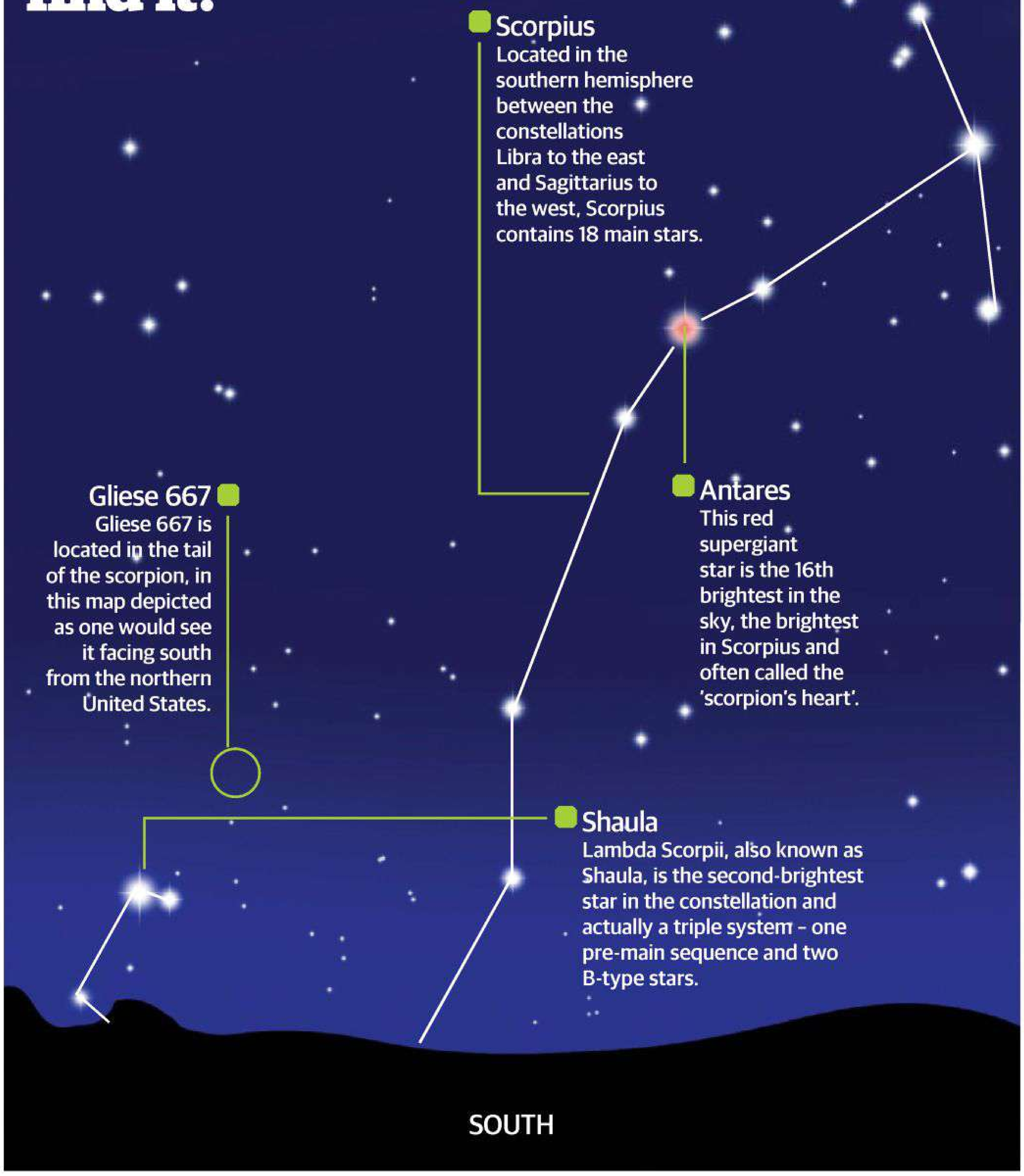
> "It's believed to have at least five, and as many as seven, planets orbiting it"



This artist's rendering of Gliese 667 C includes Gliese 667 A and B in the distance



Where do I find it?



By the numbers

105 days

Gliese 667 C completes one rotation every 105 days

6±4 billion years

Gliese 667 C is estimated to be 6±4 billion years old compared to the Sun's 4.57 billion years

1/3

Gliese 667 C has about one-third of the Sun's mass

5

Gliese 667 C has five confirmed planets in its orbit

85%

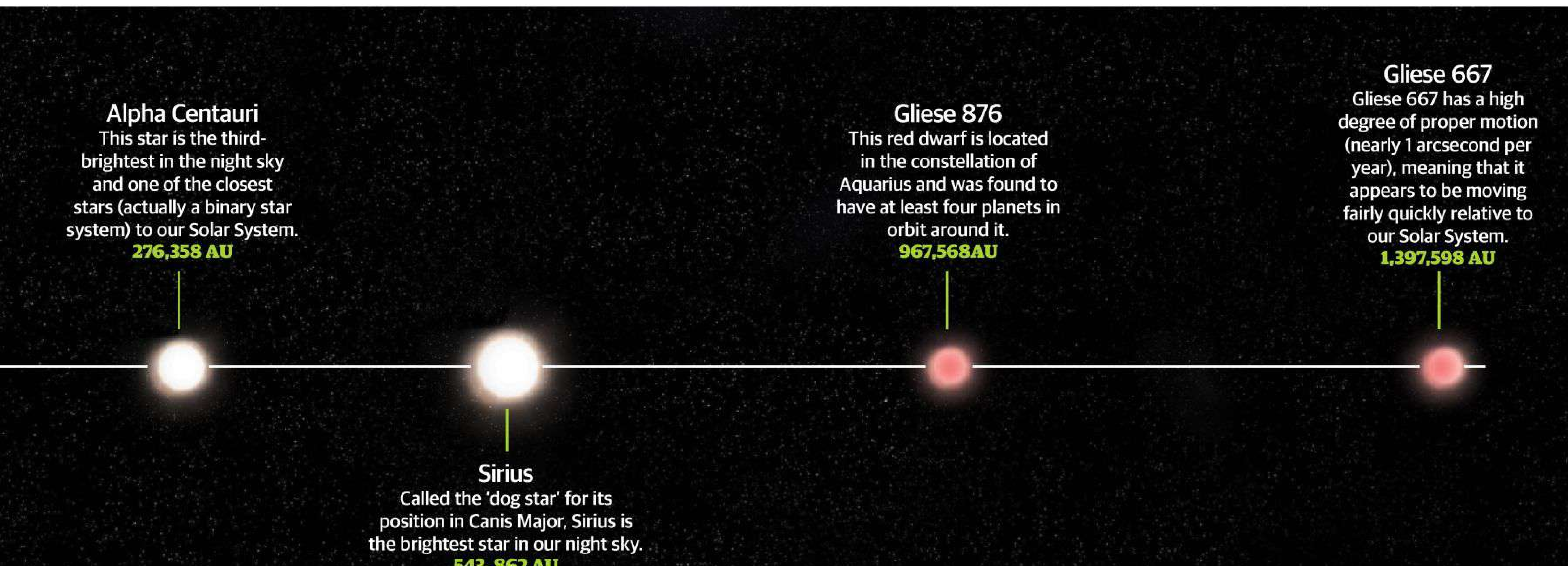
The planet Gliese 667 Cc is believed to be 85 % similar to Earth

6.5km/s

Gliese 667 C is estimated to rotate at this speed

1.4%

Gliese 667 C has just 1.4% of the Sun's luminosity



The planets around star C

With up to seven planets orbiting it, could we one day discover life in this triple-star system ?

As if having the stars Gliese 667 A, B and C wasn't confusing enough, the planets that have been discovered around Gliese 667 C also have alphabetical designations in lower case: b, c, d, e, f, g and h. Two of the planets, Gliese 667 Cg and Gliese 667 Ch, are currently unconfirmed. Three of the five confirmed planets - c, e and f - are considered super-Earths. A super-Earth is generally defined as a planet that is larger than Earth, but generally no larger than ten Earth masses, and also possesses a solid surface. Although the existence of extrasolar planets in general is rather exciting, finding ones that may be habitable - according to our Earth standards - captures even more interest.

The habitable zone - also known as the 'Goldilocks zone' - of a star is an area around the star where the temperature is 'just right'. It's neither too hot nor too cold, but has the right conditions to support a planet with an Earth-like atmosphere and liquid water. If the planet is too close to the star, then any liquid water would boil away, but being too far would mean that most of the water would be in the form of ice. The current parameters for Gliese 667 C's habitable zone extends from an inside boundary between 0.095 and 0.126 AU to an outside boundary of 0.241 and 0.251 AU. This range is roughly equivalent to the orbit of Mercury, so planets within it are much closer to the star than the Earth is to the Sun. However, since a red dwarf is a smaller, cooler and dimmer star than the Sun, planets in this small region can still be habitable.

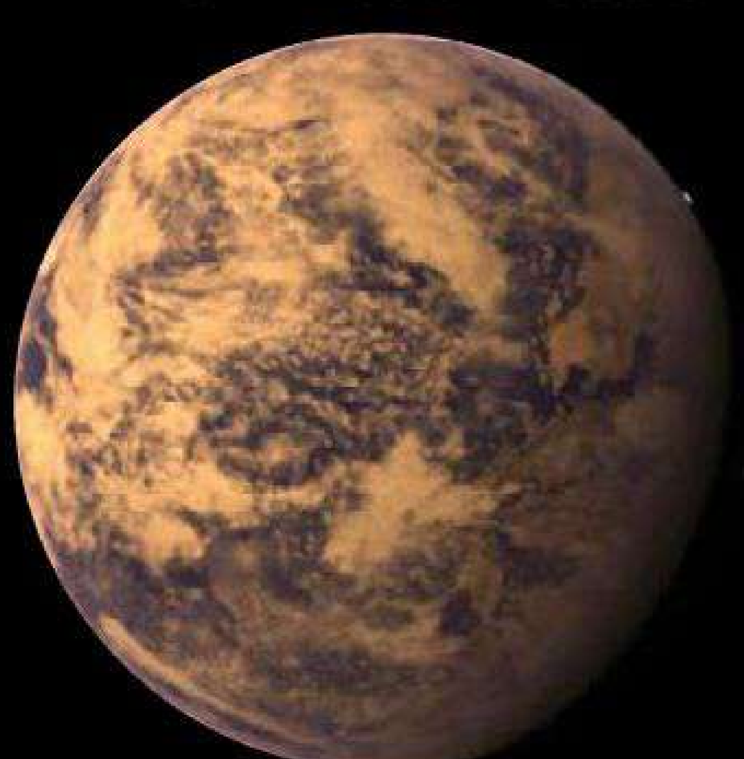
> "Gliese 667 Cc is the most Earth-like of the planets"

The first planet discovered around Gliese 667 C was Gliese 667 Cb in 2009. It is the most massive of the planets and is considered to be either a super-Earth or a mini-Neptune. The latter is also sometimes called a transitional planet or a gas dwarf; these are believed to have thick atmospheres of hydrogen and helium, with small cores surrounded by layers of ice, liquid oceans or rock. Gliese 667 Cb orbits too close to the star for the planet to be in the habitable zone. Next came Gliese 667 Cc, first mentioned in 2011 and officially announced a year later. Its mass is between 4.5 and 9 Earth masses, and it is believed to be a rocky planet located along the inner edge of the habitable zone at about 0.1251 AU. Gliese 667 Cc is estimated to have an orbital period of about 28 days, and it would get about 90 per cent of the radiation that the Earth gets from the Sun. However, most of it would be absorbed, making the planet warmer overall than the Earth, but still potentially habitable, at approximately 30 degrees Celsius (86 degrees Fahrenheit). Gliese 667 Cc is the most Earth-like of the planets found around Gliese 667 C.

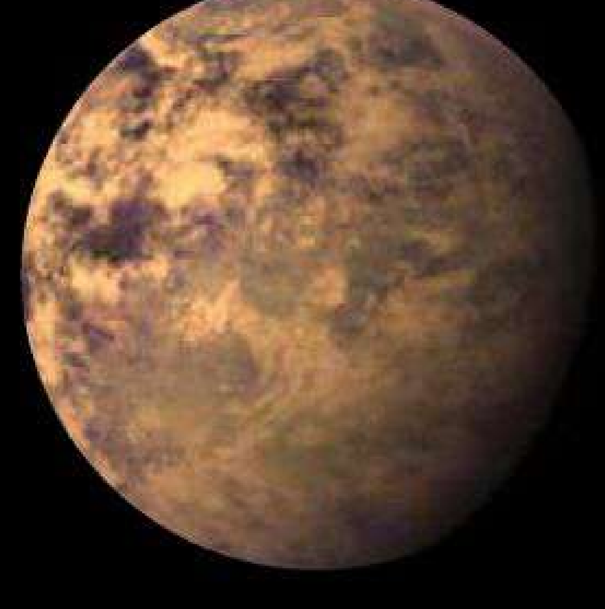
Gliese 667 Cd was discovered in 2012, and its existence was confirmed in 2013. It is slightly more massive than Gliese 667 Cc, but it's probably an icy planet because it's outside of the habitable zone while orbiting at about 0.2758 AU. Gliese 667 Cd may have a liquid water layer under its ice, however. Discovered in 2013, Gliese 667 Ce is located in the habitable zone - orbiting at a distance of 0.21257 AU - and is believed to be slightly less massive than Gliese 667 Cc. Gliese 667 Cf was also discovered in 2013, but it's directly in the middle of the habitable zone at around 0.15575 AU. Like Gliese 667 Cf, it is also a little less massive than Gliese 667 Cc.

There are also the unconfirmed planets, known as Gliese 667 Cg and 667 Ch. Both were predicted to exist prior to being announced in mid-2013. Gliese 667 Cg likely lies outside of the habitable zone and is an icy planet, with a mass somewhere between 4.41 and 9 Earth masses. Gliese 667 Ch is probably much smaller, between 1 and 2 Earth masses, and is projected to be located just outside the habitable zone - probably too close to the star. There is little evidence of the existence of Gliese 667 Ch so far. It's unlikely that there are more planets in the habitable zone of Gliese 667 C, because there are no more stable orbits available in that region.

The habitable worlds



Gliese 667 Cc
Of the three potentially habitable planets around Gliese 667 C, Cc is considered the most Earth-like. It's much bigger than the Earth - at least 4.5 times its mass - but it's believed to be similar in composition, in temperature and the amount of light received from its star.

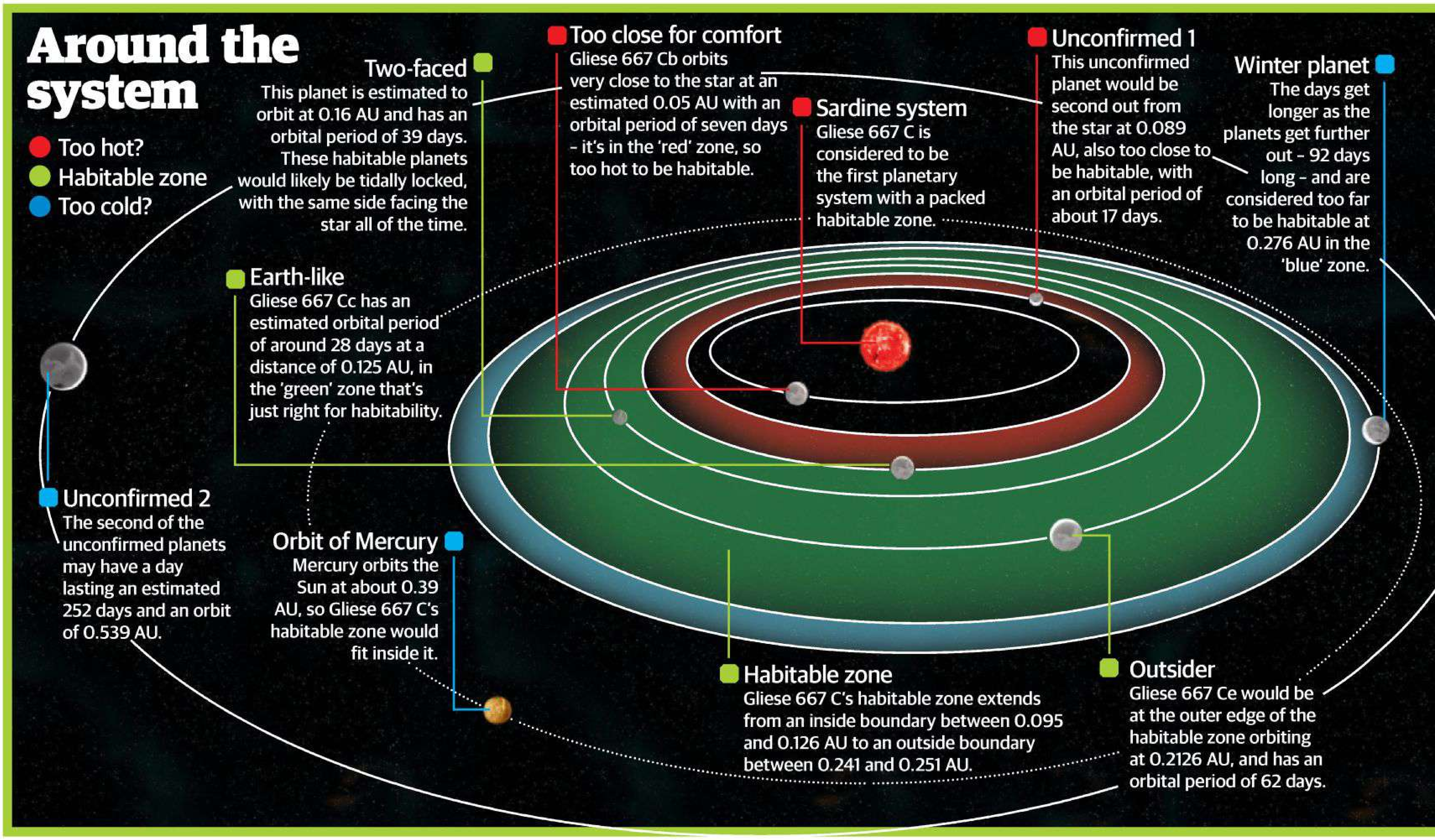


Gliese 667 Cf
This planet is smaller than Cc and is thought to be just under two Earth masses. It's in the middle of the habitable zone and should get about 60% of the starlight that the Earth receives from the Sun. But it's also thought to absorb more infrared light than the Earth and is slightly warmer.

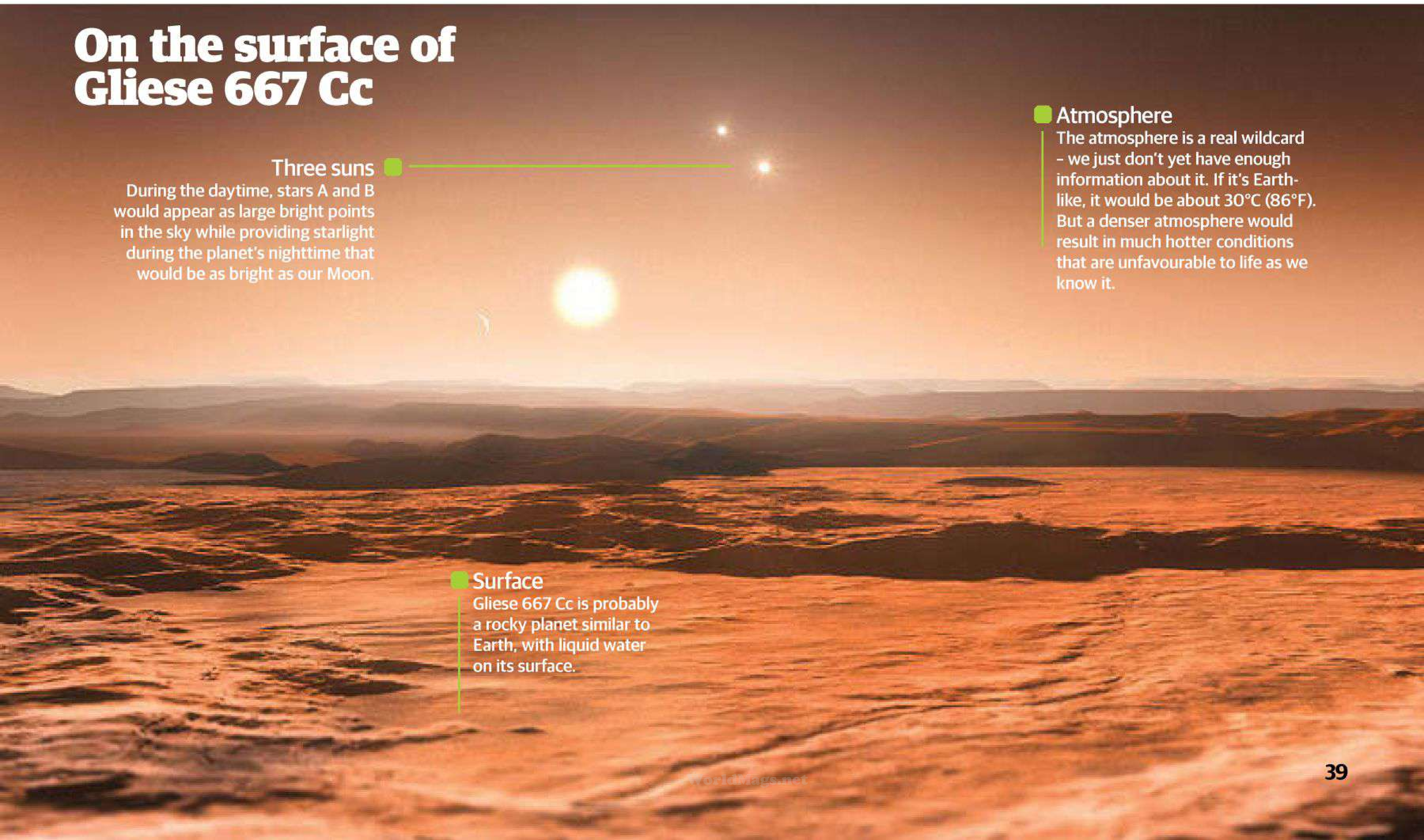
Gliese 667 Ce
Also smaller than Cc, Ce has an estimated mass somewhere between 2.5 and 3 Earth masses. Although it probably gets only a third of the starlight that the Earth gets from the Sun, if there are greenhouse gases present in its atmosphere it can still have liquid water.

Earth
It's difficult to envision that the three potential super-Earths around Gliese 667 C could have much in common with our Earth. It's important to remember that despite the designation of habitable zone, the concept of alien life existing on these planets is theoretical.

Around the system



On the surface of Gliese 667 Cc



Observing our neighbour

Exoplanet hunter HARPS is one of many instruments searching out fascinating new planetary systems

The star system Gliese 667 has been observed as a single faint star from Earth, with advances in telescope technology allowing us to differentiate between the three stars in the system. However, the planetary system around Gliese 667 C could not have been discovered without the European Southern Observatory's HARPS instrument, or High Accuracy Radial velocity Planet Searcher.

This instrument is a high-precision echelle spectrograph, which uses diffraction gratings – structures that split and diffract light into different beams – to separate incoming waves of light into a very fine frequency spectrum. HARPS uses a method called radial velocity, or wobble, to detect planets. The radial velocity is the velocity of a star or other object in the direction of our line of sight. While a planet orbits a star, the star orbits around its own centre of mass. This interaction causes the star to wobble slightly, producing Doppler shifts in the light it emits. These signals are then detected by HARPS, and they are analysed using a method known as Bayesian statistical analysis to make predictions about the potential planet's mass, orbital periods and size of orbit.

HARPS was installed on the European Southern Observatory's 3.6-metre telescope in 2002, located at the La Silla Observatory in Chile. It sits in a vacuum-sealed, temperature-controlled vessel to avoid any perturbances caused by variations in temperature or air pressure. Two identical optic fibres feed into HARPS. It is one of the most accurate and precise instruments of its kind. It has been used to discover more than 130 planets and since 2012 it has been used to detect habitable super-Earths. These days, it's considered an exoplanet super hunter due to the huge number of exoplanets it has discovered to date.

When HARPS discovered Gliese 667 Cb in 2009, within a few years enough data had been collected about the system to indicate the existence of what scientists called a 'four-planet solution' – b, c, d (unconfirmed at the time), and an unknown 'trend', with a projected long orbital period that couldn't yet be determined. This system could not be considered stable, however, and was revised to a five-planet solution in 2012 with b and c confirmed and three unconfirmed planets: d, e and f. The team believed previously that the star might be host to one potentially habitable planet. Combining the latest observations with data from other sources led the HARPS team to propose a potential seven-planet solution in mid-2013. This includes five strong signals for the planets b, c, f, e and d and the weaker signals for unconfirmed planets h and g. They also came to the conclusion that three of the planets lie in Gliese 667 C's habitable zone – an unprecedented find.

HARPS does have its limitations, however; it can only detect planets orbiting low-mass stars like Gliese 667 C. These stars are more strongly affected by the planets around them, and because their habitable zones tend to be close to the star, planets are easier to detect.

Future missions

HARPS gets the most attention for its exoplanet discoveries, but there are other instruments on the hunt for planetary systems with habitable planets. Also operated by the European Space Observatory, the Very Large Telescope – actually four telescopes – has also collected data about Gliese 667 C and is considered the most productive telescope on the ground right now. The Magellan Telescopes at Las Campanas Observatory in Chile have a Planet Search Program, and the WM Keck Observatory in Hawaii has also contributed invaluable data to the study of Gliese 667 C. There are more tools on the horizon, too. The European Space Observatory plans to install the ESPRESSO (Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations) instrument on its Very Large Telescope and have it begin receiving light by 2016. The ESPRESSO instrument is designed to be even more precise and accurate than HARPS and detect planets around even fainter stars than Gliese 667 C. There's also the Automated Planet Finder Telescope (APF) under construction at the Lick Observatory in California, intended specifically to search for rocky, habitable exoplanets orbiting stars that are less than 100 light years from Earth. There are also planned space telescopes, NASA's Transiting Exoplanet Survey Satellite (TESS) with a launch date in 2017 and the NASA/ESA collaborative James Webb Space Telescope (JWST) in 2018. TESS is meant to be a survey tool, with more precise missions investigating the most promising habitable planetary candidates.

The TESS satellite will spend two years looking at millions of stars for signs of exoplanets

> "HARPS has been used to discover more than 130 planets since its installation"

Inside HARPS

Secondary mirror
The secondary mirror in the telescope was replaced in 2004 and uses an f8 Cassegrain focus – the secondary mirror is convex. The 3.6m (140in) designation refers to the size of the telescope's aperture or opening.

Computer
This cube houses the computer used to control the telescope's secondary mirror.

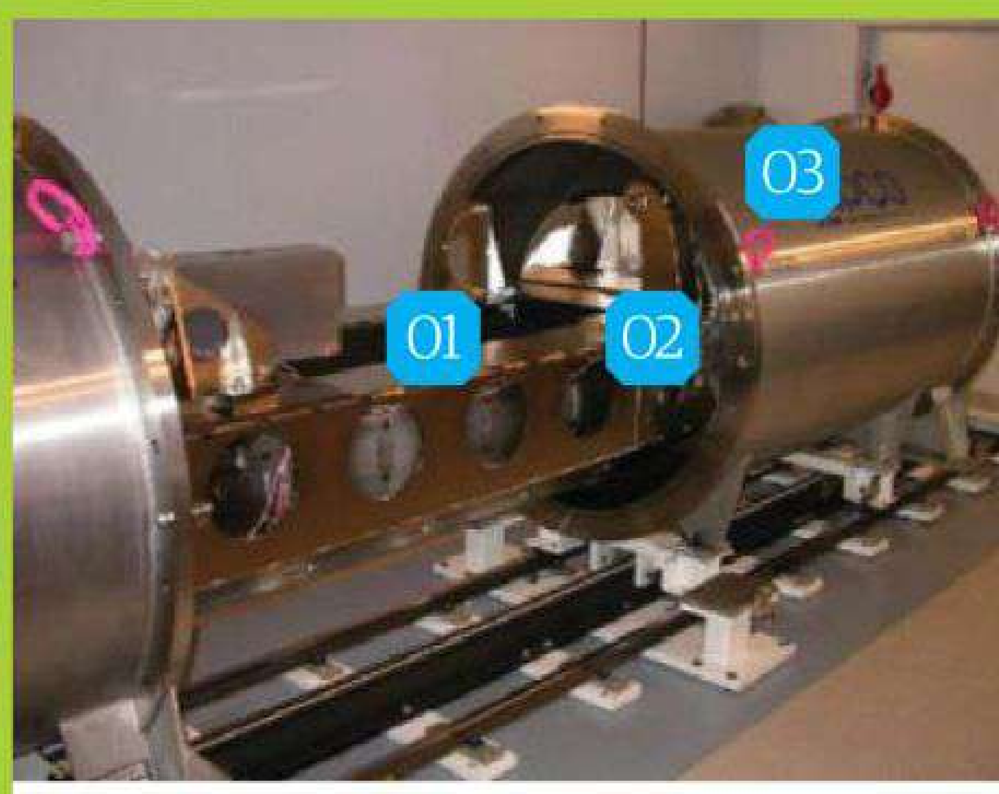
Primary mirror
This reflecting telescope uses two mirrors to gather light from the visible and near-infrared part of the electromagnetic spectrum to form an image.

Mission Profile

HARPS

Name: HARPS
Mission dates: 2003 to present
Location: La Silla Observatory in Chile

HARPS is a second-generation fibre-fed high-resolution echelle spectrograph, installed on the 3.6-metre telescope at La Silla Observatory. First used to survey stars, HARPS is now focused on the discovery of habitable super-Earths. It discovered over 50 exoplanets in 2011 alone.



1. Spectrograph
In this image you can see the echelle grating of the spectrograph, which diffracts the light received by the telescope to create an image of overlapping wavelengths.

2. Collimator
The collimator is a huge parabolic mirror (a mirror in the shape of a two-dimensional, symmetrical curve) that is used to narrow the beam of light.

3. Vacuum tube
The spectrograph for the HARPS instrument is enclosed in a vacuum vessel to maintain temperature and air pressure. The fibres carrying light from the telescope proper are fed through a hole in the side of the vessel.

New Worlds mission

By putting a huge umbrella into space, we could come closer to finding extraterrestrial life

The question of whether life exists on other planets is one that scientists frequently ponder, but have so far failed to answer. Hoping to change this is the New Worlds mission that, while still in the early phases of development following years of research, is likely to bear fruit in the near future.

One of the problems with observing extrasolar planets is the amount of light emitted by the parent star they orbit. When scientists use a telescope to look deep into space, they find the brightness of these stars drowns out the light from the orbiting planets. They still see the more-intense glow of larger planets, but the smaller ones are virtually impossible to spot. Since those tinier planets are, like Earth, more likely to contain signs of life, it means experts risk missing potential life-supporting worlds.

Dr Webster Cash, of the University of Colorado at Boulder, has devised a method to combat this problem. He proposes using a starshade, effectively a large blocker spacecraft that would be placed between the telescope and the target star. It would prevent light from the star reaching the telescope that would, in effect, be cast within a shadow. Just as a ball heading your way from up high on a bright day is better seen if you hold your hand to block the sunlight, so the planets orbiting their parent star are brought into view when the brighter light is blocked.

In 2013 NASA created a mockup of the starshade. The initial plan had been to produce a round disc, but this caused a problem with diffraction. When light from the parent star hits a round circle, it will diffract around the edge. Not only does this give a halo-like glow but it also drowns out the dimmer light of the smaller extrasolar terrestrial planets being sought, because it remains so bright.

The idea is to make the starshade look like a series of slit petals, each one sitting around the inner disk. Since the perimeter shape of the object the light is hitting governs diffraction, this design controls the way the light waves of the star behave, drastically cutting diffraction. Because the starshade will be tilted when put into space, the light from our own Sun will not disrupt the telescope's view of the extrasolar planetary system either.

Although the proposal is to fly the starshade and the telescope into space in formation, it's more likely that the telescope will be sent up first and the starshade will follow at a later date. Though a launch date is far from being confirmed, the mission concept is being put together and should be complete by 2015. The team behind it is conscious of cost – with a budget of around £1.8 billion ($3 billion) – so it'll either work with an existing collector, such as the James Webb Space Telescope, or a four-metre (13-foot) telescope likely to be built in the future.

This won't be an easy mission, as the starshade will be sent to space in a folded state before unfurling. It also needs to be aligned with a telescope around 200,000 kilometres (124,000 miles) away. With little room for error and the need to maintain alignment, so much could go wrong. If the mission enables scientists to see planets they'd otherwise miss, enabling them be to analysed for water vapour, carbon dioxide and oxygen, the big question of the universe could be answered soon.

> "It needs to be aligned with a telescope around 200,000 kilometres away"

Viewable planets
This planet wouldn't be seen if the starshade weren't placed in front of it. Instead it would emit a dim glow that would be outshone by the star.

The star
When using a telescope to find extrasolar planets, the incredible glare from the parent star makes it impossible to see smaller, close-orbiting planets.

Starshade
The mission will fly the starshade into space. Once it unfurls, it will look like a gigantic flower, casting a large shadow behind it.

Star light
The petal shapes prevent bright spots that would otherwise mask the planets orbiting the star, creating a far dimmer glow.

Petals
If the starshade were round, diffraction would occur and the rippling light would still hamper the telescope's vision, so petals solve the issue.

Taking images
This is how the starshade looks from the telescope. It can take images of the planets that it spots at the sides of the starshade.